

NIST-GCR-89-562



Fire Risk Analysis Methodology: Initiating Events

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February 1989
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U.S. DEPARTMENT OF COMMERCE
National Institute of Standards and Technology
(Formerly National Bureau of Standards)
Center for Fire Research
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NIST Grant No. 60NANB6D0649



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Prepared for
U.S. DEPARTMENT OF COMMERCE
National Institute of Standards and Technology
(Formerly National Bureau of Standards)
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This report was prepared for the Center for Fire Research of the National Institute of Standards and Technology under Grant Number 60NANB6D0649. The statements and conclusions contained in this report are those of the authors and do not necessarily reflect the views of the National Institute of Standards and Technology or the Center for Fire Research.

Final Report to
Center for Fire Research
National Institute of Standards and Technology

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ABSTRACT

This report outlines a method for assessing the frequency of ignition of a consumer product in a building and shows how the method would be used in an example scenario utilizing upholstered furniture as the product and radiant auxiliary heating devices (electric heaters, wood stoves) as the ignition source. Deterministic thermal models of the heat transport processes are coupled with parameter uncertainty analysis of the models and with a probabilistic analysis of the events involved in a typical scenario. This leads to a distribution for the frequency of ignition for the product.

I

INTRODUCTION AND SUMMARY

The fire problem in the United States consists of fires which occur in many different areas, such as forest fires, industrial plant fires, residential home fires, and vehicle fires. The consequences of fires in any of these areas may be categorized as: dollar loss, deaths, and injuries. In human terms, the highest cost of fire is deaths. In 1986, there were 5850 civilian (as opposed to firefighter) deaths from fire in the United States [1].

The assessment of the risk from these fires is essentially the calculation of the probability of consequences occurring from some defined hazard. In our case, the consequences are death, injury or property loss, and the hazard is a fire. A method for modeling the risk of deaths from fires has been proposed in [2-3]. For existing products and conditions in buildings, the summary equation for the model is:

$$E[\text{deaths}] = \sum_{\text{TD}} F_{\text{TD}} \sum_i P(S | \text{TD})_i \sum_j D_{ij} P(O | \text{TD})_j \quad (1)$$

where

- $E(\text{deaths})$ = expected number of deaths
- F_{TD} = total fires per occupancy by time of day.
- $P(S | \text{TD})_i$ = probability of fire scenario i given time of day.
- D_{ij} = deaths per fire given i and j , based upon the hazard model result.
- $P(O | \text{TD})_j$ = probability of occupant set j given time of day.

The first factor, F_{TD} , can be derived from statistical evidence involving the occupancy type under analysis. A major source of data for this analysis is the NFIRS data base [4], which is based on the NFPA 901 reporting standard for fires. The second factor, $P(S | TD)_i$, is composed of several different parts which include: the type of building in which the fire occurs, the room in which it starts, whether or not a product being analyzed is the first item ignited or not, and the extent of flame propagation assumed for the fire. An estimate of the proportion of all fires which apply to each of these parts is available from [4].

The third factor, D_{ij} , is a calculation of the number of deaths from a given fire scenario using the hazard model described in [5]. The hazard model is an integrated set of deterministic computer models which describe the physical progress of the fire scenario from ignition to occupant escape or death. $P(O | TD)_j$ is the probability of a certain set of occupants being in the building at a certain time of day. This number is estimated from sources such as U.S. census data.

The portions of this scenario analysis in which we are interested in this work involve the factors F_{TD} and $P(S | TD)_i$. These factors characterize the scenario's initiating events (IEs) and the processes which interact in time. A logical depiction of the competition in time between events during a fire's development is given in Figure 1.

This event tree is a high level depiction of the processes which compete during a fire. After the initial ignition of the first item, the processes of fire growth, detection and suppression interact to produce a variety of possible scenario outcomes, depending upon the specific events which actually take place during the fire. Since these events are not all deterministic in nature (e.g., due to the inherent nature of a mechanical device, there is some probability that a smoke detector will not function even if our deterministic

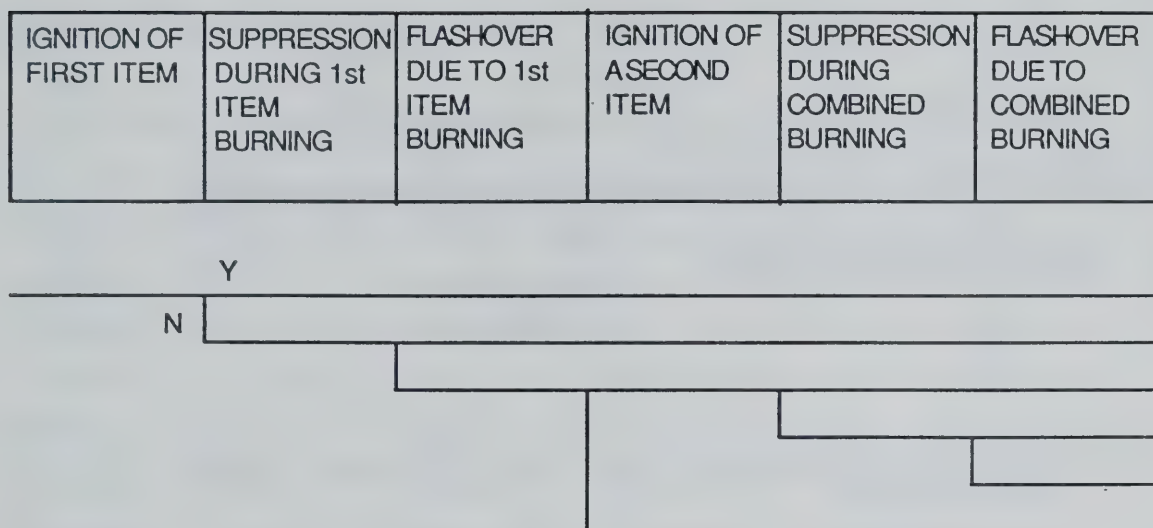


Figure 1: Fire Propagation Event Tree

analysis says that it should), they must be described by probability distributions. One realization of this competition is shown in Figure 2. The time line extends to the right, the fire is detected during the burning of the first item ignited, but is not suppressed until after the second item ignition (but before room flashover). This, of course, is only one possibility out of many.

A major goal of the work in [2] is to be able not only to model the risk from the mix of existing products, but to enable an analyst to predict changes in that risk which occur from the introduction of a new product.

In [6], it is noted that it is the contents of a building and not the structure itself which often cause and fuel residential fires. In fact, smoking materials are the leading cause of fatal residential fires [6]. Smoking materials generally ignite soft goods such as bedding, upholstered furniture, clothing, etc. Heating and cooking equipment are the second largest cause of fatal home fires. A

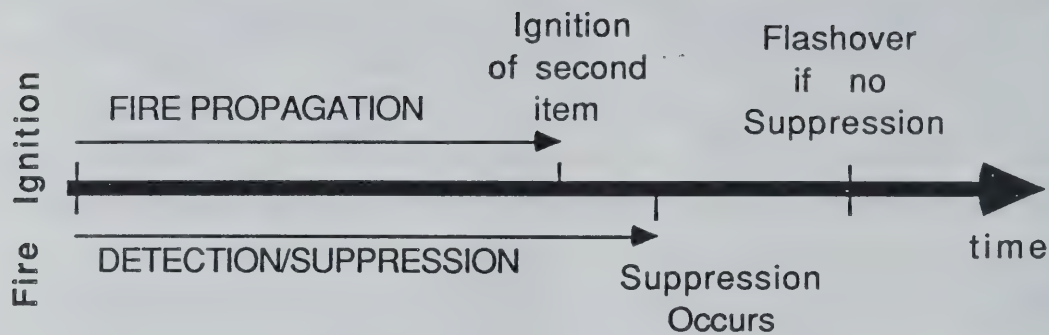


Figure 2: A realization of the competition in time of fire growth, detection and suppression.

variety of materials, such as clothing and other soft goods such as upholstered furniture, creosote (build-up in chimneys), and cooking materials (grease) are involved in fires ignited by heating and cooking equipment [6].

Upon the introduction of a new material into a fire scenario, relevant material properties which may change the progress of a fire scenario and thus increase or decrease the risk to property/persons are:

1. The product's "ignitability"
2. The product's rate of heat release (RHR) once ignited (rate of rise of the RHR, peak RHR).
3. The product's combustion product characteristics (amount of smoke, toxicity of the combustion products, etc.).

These factors interact in complex ways during a fire scenario, and improvements in one may be offset by the degradation of others (e.g., less heat release, but more toxic combustion products). It is difficult to tell a priori whether a new product will increase or decrease the risk without a formal

analysis of the interactions which occur during a fire scenario. This work develops a model for the primary ignition frequency of a consumer product.

The frequency with which a fire begins is an important input to the analysis of a fire scenario. In the previous discussion, the combination of all of the possible frequencies from different product and ignitor combinations is combined in the F_{TD} factor. For a specific product under analysis, the frequency with which the product is the first item ignited is a relevant input to the $P(S | TD)_i$ factor as well as to the total frequency of fires. For many building/room/material combinations, fire occurrence data give us various statistics to work with, including the frequency of primary fire ignition involving the material. However, when a new product is introduced and an analysis is being performed on a scenario involving it, the applicability of statistics which describe other materials is subject to doubt. This is because physical/chemical/thermal changes in the material may cause it to become either easier or more difficult to ignite. The pertinent question then, is how would these statistics change if a product's "ignitability" were to change.

Inherent in a fire scenario is the knowledge that somehow an ignition source transferred enough heat to some item to cause that item to begin burning (to ignite). Given a particular target item and ignitor (as well as building type, room, etc.), statistics exist (NFIRS [4], NFPA [7]) on the frequency with which an ignitor caused a fire by igniting that item. At a higher level, the number of fires that the ignitor caused by igniting any item is also available. In many instances there is also information on how the ignitor came to ignite the item. Thus we know, for the status quo products and ignition sources, a variety of statistics on the 'average' time rate of occurrence of fires involving them.

If we define ignitability as the fraction of ignitions of the item given exposure (yet to be defined) to the ignition source

($f(\text{ign. before intervention}|\text{exp})$, or $f(\text{ign. b.i.}|\text{exp})$), and defining $fr(\text{exp})$ as the frequency with which the product is exposed to the source, we have the frequency of ignition of the product given as:

$$fr(\text{ignition}) = fr(\text{exp})f(\text{ign. before intervention} | \text{exp}) \quad (2)$$

where the value of $f(\text{ign. b.i.}|\text{exp})$, the fraction of ignitions of the product which occur before any type of intervention in the scenario (such as burning out of the ignition source, or an occupant moving the ignition source away), given exposure to the ignition source, will be a function of physical modeling and experimental evidence for either an old or a new product. We will simply call this the $f(\text{ign}|\text{exp})$ from here on. For the status quo, we have data on $fr(\text{ignition})$, but not on $fr(\text{exp})$. For a new product, we have neither $fr(\text{ignition})$ or $fr(\text{exp})$. It is $fr(\text{ignition})$ for the new product case which we wish to assess.

To illustrate the method clearly, we have chosen a specific ignition source and product item combination to use in the calculations. We have chosen upholstered furniture; specifically a cotton/polyester cover fabric used to cover upholstered furniture as our example consumer product, and alternative heating devices (e.g., portable electric space heaters, wood stoves) as the example ignition source. Reference 8 identifies four types of alternative heating devices which are important to the occurrence of fires and deaths in residences in the United States. These four heaters are: portable electric heaters, portable kerosene heaters, fixed gas fueled heaters, and wood stoves. We are going to physically model these four types of heaters as either rectangular or cylindrical radiating areas such as is shown in Figure 3.

As can be seen in Figure 3, the electric heater and the gas heater are modeled as radiating rectangular areas of length L and width W and the kerosene heater and wood stove are modeled as cylinders of radius R and height H . The radiative thermal power of all four heaters is characterized by the total heater radiative power output P . The values of these geometrical and thermal variables are obtained from experimental results, surveys of existing

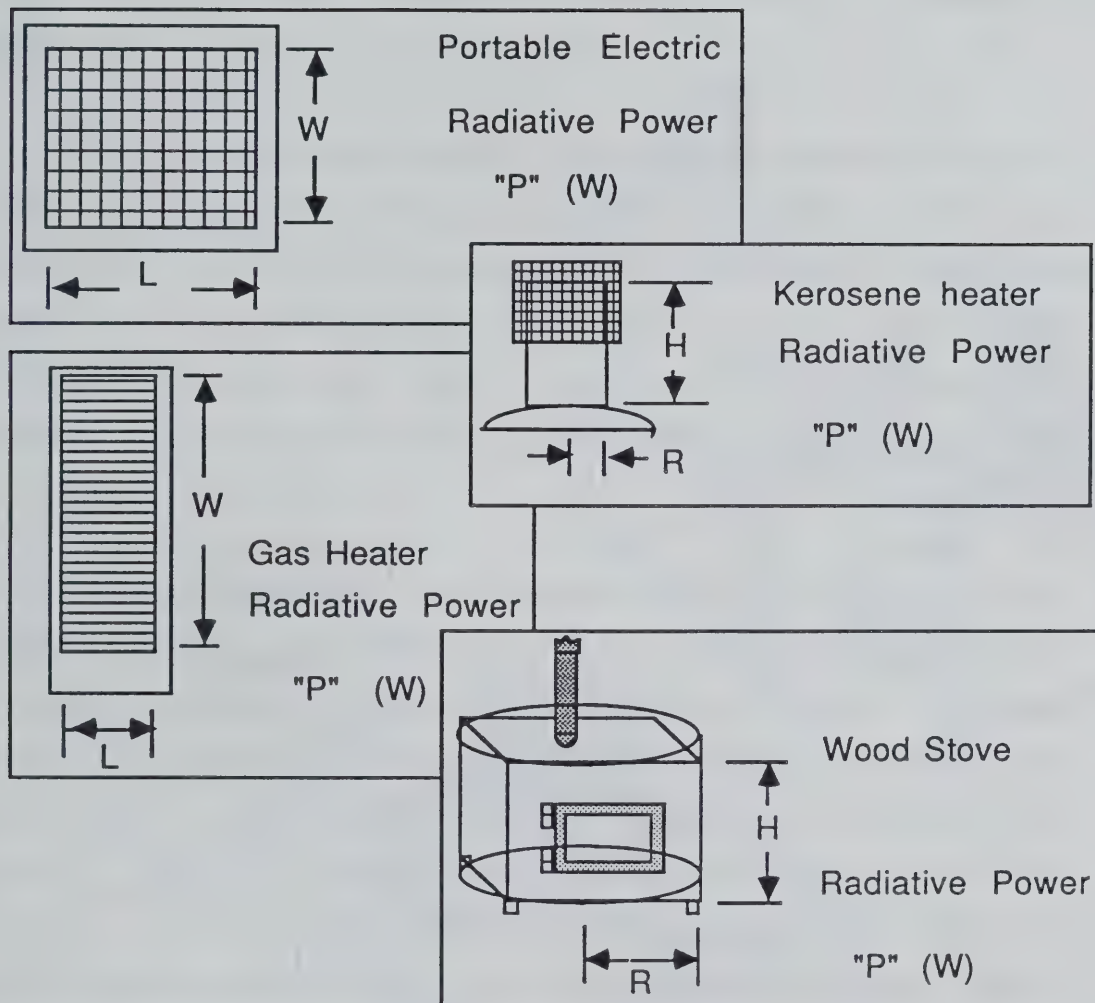


Figure 3: Models for four types of heating devices.

heaters and physical calculations. Much more detail on the heat transfer from the heaters and the values of L , W , R , H , and P is given in Sections III and IV.

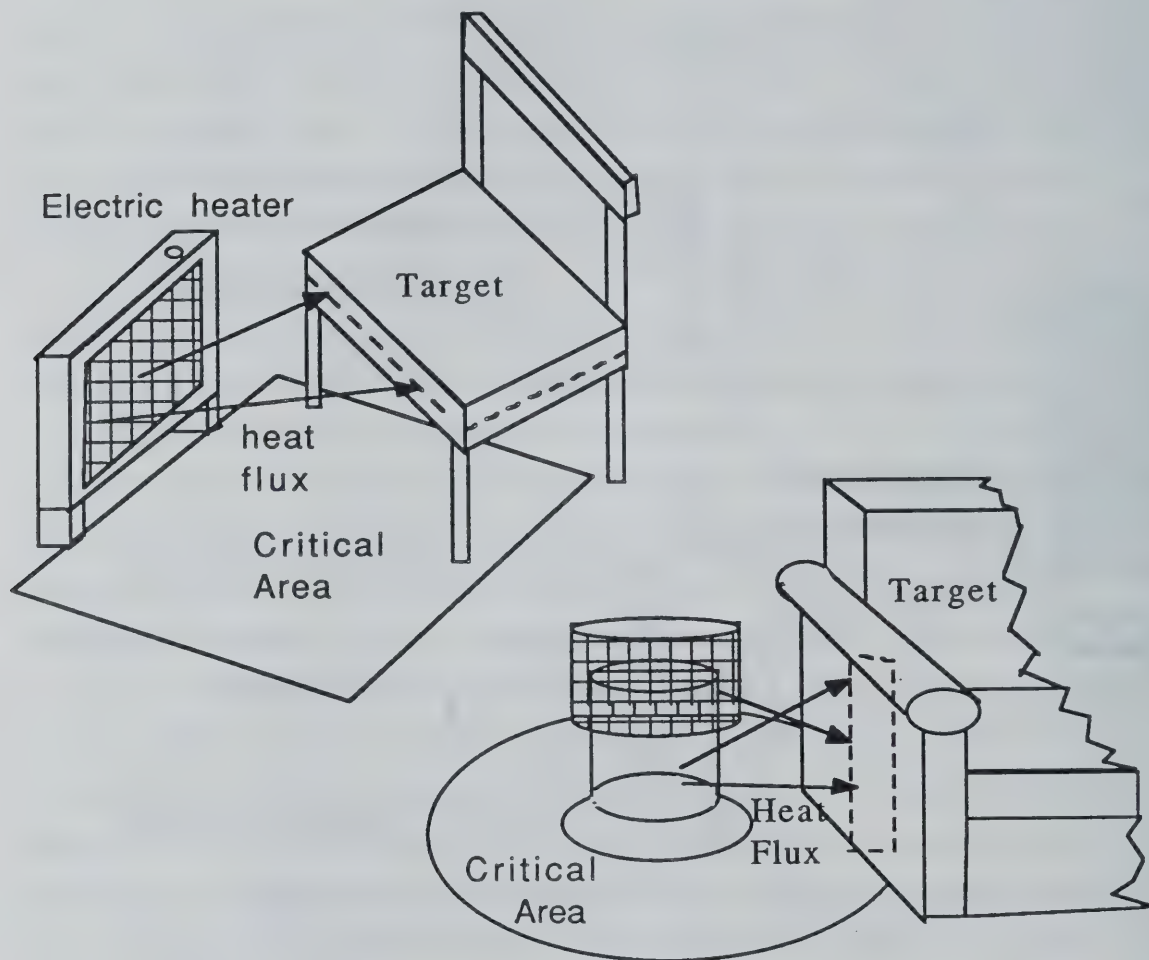


Figure 4: Heater to target geometry and critical areas.

The physical relationship between a heater and a piece of upholstered furniture is shown in Figure 4. As shown by the dotted lines in Figure 4, the target is actually modelled as a two-dimensional slab. This slab is taken to be homogeneous and has constant thermal properties. A computer code has been

developed to model the heat transfer from the heater to the target and is described in Section III. Using the homogeneous slab model of the target to model a fabric covered upholstered furniture cushion is described in Section 4.2.

In front of a rectangular radiator and around a cylindrical radiator is defined a "critical area" (as shown in Figure 4). The boundary of this area is defined by the distance from the heater at which the heat flux at the target object would drop below $5 \text{ kW}/m^2$. This value is based on experimental evidence of the approximate heat flux at which no upholstered furniture cushion would be expected to ignite [9]. The basis for this value is discussed in Section 4.3.1 and Figure 22.

This critical area definition also defines our meaning of "exposure" of the target to the heater. We define exposure to mean that some part of the target is within this critical area in front of or around the heater. Two other descriptions of the scenario are necessary to define the heater/target interaction. These are descriptions of when (or how often) the target will be within the critical area in front of a heater and where within the critical area it will be. To define the frequency with which the target will be somewhere within the critical area, we define the frequency of exposure $fr(exp)$, which is based on statistical evidence from fire occurrences and consumer product accidents as described in Section II. The frequency of exposure for a new product can be assumed to be the same as in the status quo product case even when a new product is introduced, since the new product can be assumed to not affect people's attitudes and ways of acting. (This is not strictly true, since if a supposedly "fireproof" article is introduced, it may tend to make people more careless. However, people would have to be made very aware of this "fireproof condition" in order for it to have an effect.)

To define the position of the target within the critical area when it is exposed to the heater, we make the assumption that the position of the closest point of the target to the heater is distributed uniformly within the critical area. This is a fairly conservative assumption since people would probably tend to place combustible objects farther from the heater rather than closer. Thus, we also investigate the effect of using a linearly increasing distribution (triangular as in Figure 5) for the distribution of position within the critical area. See Section 4.4 for more detail on these assumptions.

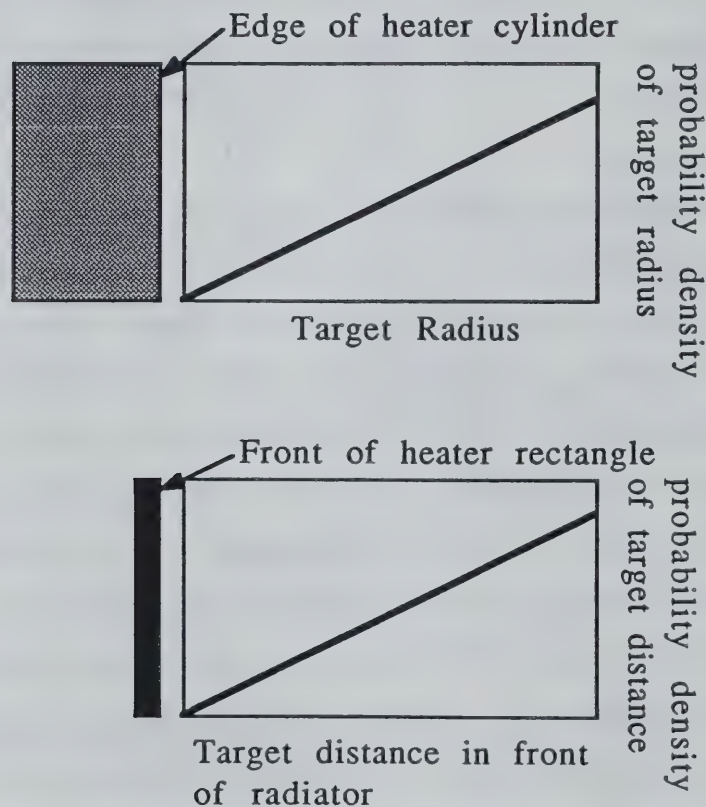


Figure 5: Triangular distribution of position within the critical area.

Thus far we have defined all of the physical and probabilistic values needed to define where and when the target will be in the critical area in front of a heater as well as being able to describe the geometrical and thermal properties of the target and each type of heater. Now we need to assess the value of $f(\text{ign}|\text{exp})$, the fraction of ignitions of the target given exposure to the heater before any type of intervention occurs.

Existing in the United States today is a "set" of pieces of upholstered furniture which have been manufactured in past years and are still in existence. This set of furniture pieces has certain characteristics of its cover fabrics and padding materials which we may estimate with a simple calculation (See Appendix C.4). What we will do with this set of furniture pieces is assume that all of them will be recovered with the cotton/polyester fabric which we are analyzing, but keeping the existing distribution of padding types since we are not analyzing the effects of changing the padding type. There also exists a set of existing heaters of the four types we have described. Estimates of the number of these existing heaters is obtained from [8]. Since we are attempting to estimate the frequency of ignitions of our target in any residential dwelling within the U.S., and are not attempting to assess any house-to-house variability in the existence of certain heater types or pieces of furniture, we can assume that any of the pieces of furniture in the "set" of pieces of furniture may be exposed to any of the existing heaters.

Thus we have several unknowns which must be assessed when we are calculating a value for $f(\text{ign}|\text{exp})$. Essentially, these unknowns fall into three categories: 1) which chair of the set of chairs is being exposed to a heater, 2) which heater type is the chair being exposed to and what are the heater's characteristics, and 3) the placement of the piece of furniture in relation to the heater within the critical area. These are all "state-of-knowledge" unknowns since for a given exposure of a piece of furniture to a heater somewhere within the U.S., the actual characteristics of the furniture, the heater type, and the

geometry between them are set values, we just don't know what these values are. To assess the effects of these state-of-knowledge uncertainties, the procedure is as follows (also graphically depicted in the flowchart shown in Figure 6):

1. Select a piece of furniture from the set of furniture by sampling from the relevant distributions describing the thermophysical properties of the furniture covering and padding (surface emissivity, ignition temperature, thermal conductivity, specific heat, and density).
2. Select a heater type and the physical characteristics of that heater from the relevant distributions for the different types of heaters.
3. Select the physical placement of the piece of furniture with respect to the heater within the critical area using the uniform or triangular distribution assumption discussed above.
4. Using the computer code, calculate the thermal response of the furniture cushion and see if and when the ignition temperature is exceeded. If it is exceeded, then this scenario contributes an ignition to the $f(\text{ign}|\text{exp})$ calculation for this piece of furniture.
5. Using the same description of the piece of furniture, repeat steps two through four to generate another ignition/non-ignition trial.
6. After a suitable number of trials (See Section 4.4), the number of ignitions observed divided by the number of trials is an estimate of the $f(\text{ign}|\text{exp})$ for this piece of furniture.
7. Repeat steps one through six to generate another estimate of $f(\text{ign}|\text{exp})$ for another piece of furniture from the set of furniture. Repeat this for a suitable number of pieces of furniture (See Section 4.4) and thus generate a set of estimates for $f(\text{ign}|\text{exp})$ for the set of furniture throughout the U.S. with the cover fabric we are analyzing. This set of values is a sample from the state-of-knowledge uncertainty distribution of $f(\text{ign}|\text{exp})$ for the set of furniture. Thus, from this sample, we form the distribution of $f(\text{ign}|\text{exp})$.

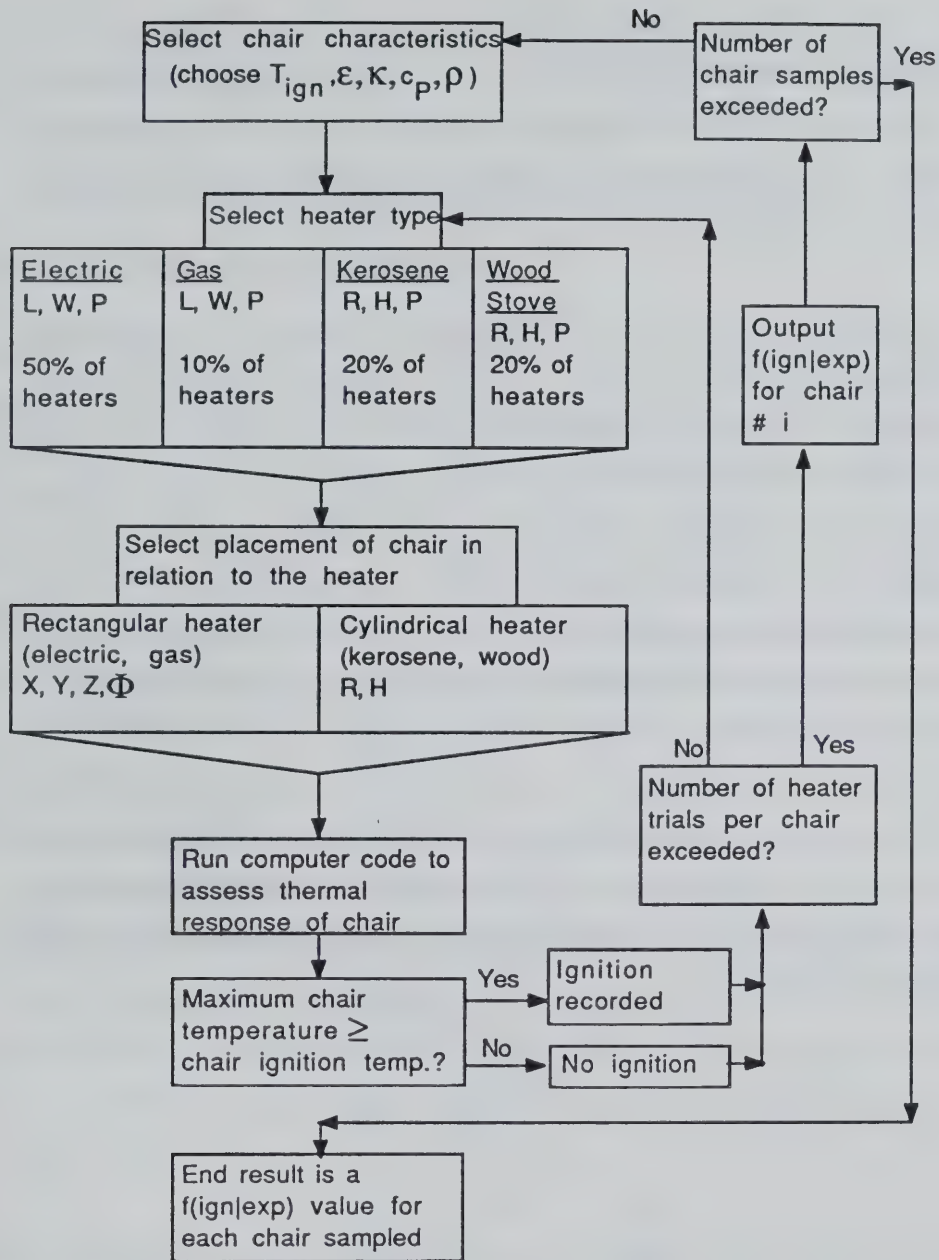


Figure 6: Flowchart of the ignition scenario selection process.

Now that we have defined the distribution for the $fr(exp)$ and for the $f(ign|exp)$, we may calculate the distribution of the $fr(ignition)$ by using

Equation 2. This value is actually a distribution of the upper bound of the $fr(ignition)$ because we are not considering any occupant effects on the ignition scenario. Occupants in the dwelling may interrupt the ignition process in a variety of ways. These effects are discussed in Sections II and 4.5, but are not quantified in this work.

The above steps in the calculation of $fr(ignition)$ are general in nature even though we illustrate them with a specific example of ignitor and target product. Any other ignitor and product combination could be modeled in the same manner by assessing the ignitor's specific $fr(exp)$ distribution and providing a model for the physical processes involved in the ignition process in order to assess $f(ign|exp)$. One could also assess the $fr(ignition)$ from heaters for some other new product by changing the target product thermal characteristics and using the computer model to model the new product form (the two dimensional target model is able to model a variety of target sizes).

Thus, we see that even though the specifics of the physical calculations, the assessment of the distributions for all of the state-of-knowledge uncertainties, and the final calculation of the $f(ign|exp)$ seems quite specific, the underlying idea is actually quite general.

II

NEW PRODUCT INITIATING EVENT FREQUENCY

2.1 THE FREQUENCY OF EXPOSURE

The value of $fr(exp)$ could be interpreted in one of two ways. These interpretations involve the exposure intensity and duration. The intensity is important since for most materials, there is some minimum intensity of exposure below which the material will not ignite (a 100W light bulb may ignite a piece of tissue dropped on it, but not a piece of wood in contact with it.) Duration is important for all scenarios since even a very intense source may not cause an ignition if it is only briefly exposed to the product (someone places a cardboard pizza box on an electric burner, quickly realizes one's mistake and removes it.) Thus, the two possible interpretations of $fr(exp)$ are as follows:

1. the frequency with which the product is exposed to the ignition source for any length of time or intensity of exposure.
2. the frequency with which the product is exposed to an ignition source of adequate intensity and duration to cause ignition (product dependent).

In 1), the ignition source intensity and duration information will have to be combined in $f(ign|exp)$ in a meaningful way. In 2), an initial analysis would have to be performed to screen out any nonsignificant events, and would then be a product dependent value.

Utilizing interpretation 1) gives us:

$$fr(ignition) = fr(exp) f_{sufficient} f(ign|exp) \quad (3)$$

$$f_{sufficient} = f(I > I_{mat} | \text{exp}) f(t > t_{ig,I} | I > I_{mat}, \text{exp}) \quad (4)$$

$$f(t > t_{ig,I} | I > I_{mat}, \text{exp}) \simeq f(\text{no burnout, no removal, no suppression}) \quad (5)$$

where

- $f_{sufficient}$ is the fraction of exposures which are of sufficient intensity and duration
- I = intensity (heat flux in W/m^2)
- I_{mat} = material dependent minimum exposure intensity for ignition
- $t_{ig,I}$ = time of ignition given intensity I .

These three equations incorporate the physical and probabilistic processes which are required to cause an object to ignite. Equation 3 splits the original $f(\text{ign}|\text{exp})$ from Equation 2 into two parts; $f_{sufficient}$ and a new $f(\text{ign}|\text{exp})$. This definition of $f(\text{ign}|\text{exp})$ contains the uncertainties in all the physical variables in the scenario such as the thermal properties of the material being analyzed and the distribution of the incident heat flux. Separated out of the original definition is the factor $f_{sufficient}$ as shown in Equation 4. The first component of $f_{sufficient}$, $f(I > I_{mat} | \text{exp})$, is the fraction of exposures of the material to the ignition source where the incident heat flux is greater than a “minimum heat flux for ignition”. For a variety of furniture materials, this minimum heat flux has been established [9]. The second component of $f_{sufficient}$, $f(t > t_{ig,I} | I > I_{mat}, \text{exp})$, as shown in Equation 5, involves the fraction of the exposures in which ignition could occur because of the intensity of the source, and where the exposure time is also long enough for ignition to occur. The exposure of the material could be interrupted by the heat source being removed (by either a person or burning out such as a wood stove) or the material being removed (by a person).

This definition of $f(\text{exp})$ is still fairly nebulous since, if a wood stove in the center of a room is hot, then all items in line- of- sight to the stove are actually

being "exposed", notwithstanding that they may be 15 feet away! Thus, we need a better definition of this factor.

The class of ignitors which we have chosen to illustrate the method, "fixed or portable area heaters", consists of several different forms and fuel types. Fuels can be gas, liquid, solid or electric. Solid fuels are almost exclusively wood, liquid fuels are dominated by kerosene, and gas is usually propane or natural gas. Fixed heaters range from small electric wall or baseboard units to medium/large wall gas units, to wood-stoves and fireplaces (normally wood-fueled). Portable heaters are usually small (hence portable) and either electric or liquid fueled. A look at how fixed and portable heaters "expose" products provides useful insights.

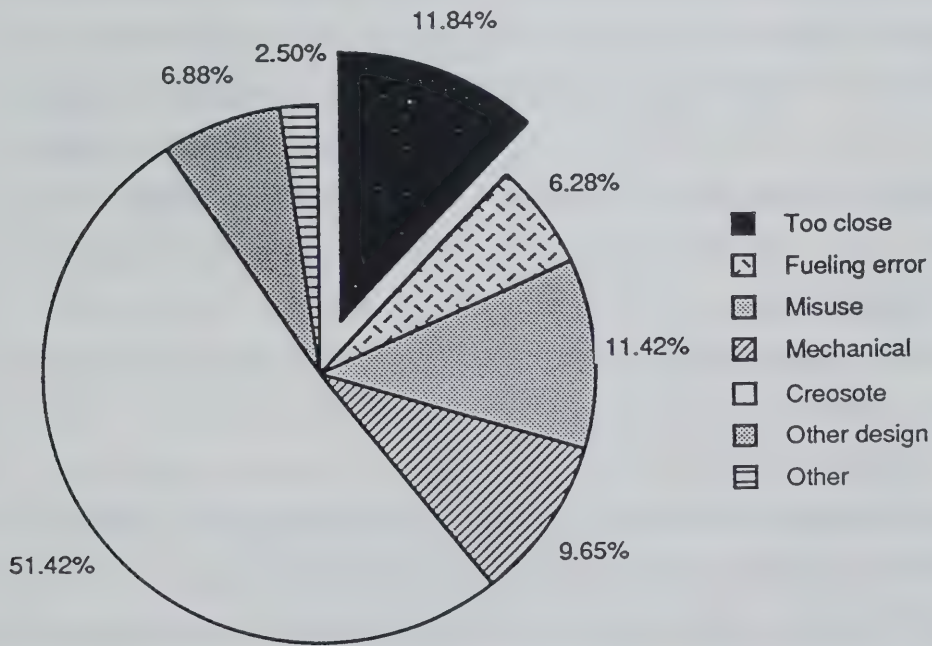


Figure 7: Percent Fire Causes for Area Heaters, 1985 data [8,10]

Figure 7 shows the various percent causes for the seven "ignition" factors discussed in the list below. (The category definitions are taken from [10] while the data is from [8].) We wish to limit ourselves to fires which fit the following

criteria: involve consumer products (as opposed to structural materials) and those for which the frequency of occurrence may change by changing the product. An example of a class of fire which does not fit these criteria is the "creosote" category since it involves fires in chimneys and surrounding structural material instead of a consumer product. Looking at the seven categories of ignition factors closely, we find the following:

1. "Misuse," includes inadequately controlling the equipment, leaving it unattended, overloading it, knocking it over, and starting it up or shutting it off incorrectly.

This category involves mainly allowing the equipment to operate outside its safe range (inadequate control, overload) or otherwise causing the device to operate improperly. Such conditions as overheating and knocking the device over can be expected to expose products close to the device to a severe environment. This would tend to diminish flammability differences between products since most products, when exposed to a severe thermal environment may be expected to ignite.

2. "Mechanical," includes part failure, control device failure, short circuits and other mechanical and electrical failures.

This category may be affected by failures which do not cause very severe environments, but failures which cause overheating, fuel spillage, etc. are subject to the same arguments as in the Misuse case.

3. "Creosote," build-up and other maintenance failures. This category applies to solid-fueled devices only and was created to combine "lack of maintenance" and "unclassified operational deficiency," which appear to be the principal codes used to denote creosote build-up due to insufficient maintenance. This is a very common problem that is difficult to fit into the NFPA 901 codes.

This category involves mainly chimney fires and structural materials.

4. "Fueling error," includes fuel spills, the accidental release of fuel, and the use of the wrong fuel.

This category involves released flammable liquid causing a fire. Very few products may be expected not to ignite with burning kerosene spilled on them.

5. "Item too close," and "installed close." For fixed devices, it makes sense to separate fires in which the device is installed too close to something, usually a structural member from fires in which a movable combustible such as bedding is placed too close to the heater. For portable devices, the distinction is not useful, and the two categories are combined.

This category involves placing the heater too close to an item or an item too close to the heater and heat being transferred by radiation or conduction (in the case of touching). A material's resistance to radiant ignition may be changed and thus this category may be affected by product changes.

6. "Other design" denotes an error in the design or installation of the heater, other than installing it too close to something.

This would indicate a malfunctioning heater which would expose products to a severe environment as in the Misuse category.

7. "Other." The effects here are unknown.

Thus, we see that of the seven categories, only #5, "Item too close" and possibly #2, "Mechanical", may have their frequencies of ignition changed by a change in consumer products. If we assume that any product which is placed in direct contact with a heating element or flame can be assumed to quickly ignite, and that the mechanical category will cause severe environments which would lessen apparent ignitability differences between materials, we are essentially left with radiant ignition of a product placed too close to the heater as our only important mode of changing the number of fires due to space heaters by changes in consumer products.

The preceding discussion suggests that the type of scenarios of most importance to study for the purposes of assessing the change in ignition frequency of a new product exposed to heating devices are ones in which a person places a combustible too close to a heater or visa versa. This restricts the range of $fr(exp)$ which we need to consider, but it still does not adequately define it.

It seems unnecessary to define $fr(exp)$ in terms of a separation distance since it would be product dependent again. The value either needs to be estimated from statistics which describe fires in general or heater fires specifically, or possibly from statistics describing people's tendency to have accidents involving consumer products. We will look at heater fire statistics first.

A set of data from 1985 as given in [8] is shown in Table 1. This shows the number of fires by heater fuel and type. Table 1 is a synopsis of the data on individual heater types and the fire causes presented in Table 2 [8]. All of the data here are for heater fires which occurred in residential dwellings in the U.S. during 1985. In 1985, there were approximately 88,000,000 households in the U.S. This translates to a rate of occurrence of fire per household due to something coming too close to a space heater (by whatever method) of $7259/88000000 = 8.3 \times 10^{-5} \text{ yr}^{-1}$ per household (7259 is the "too close category" from Table 1). This is the minimum number of times that an exposure of a consumer product to a heating device occurred in 1985. This number utilizes only the "too close" category. If we also include the "mechanical" category, the number is $1.4 \times 10^{-4} \text{ yr}^{-1}$ per household, which is not a significant difference. This number implicitly assumes that only one of these fires occurred per household in the year 1985. For these fires, i.e., fires which are reported and show up in the data base, we may assume that they are reasonably severe (probably necessitate calling the fire department). Thus, it is reasonable to assume that the occupant's actions would be changed so as to preclude a

similar occurrence (at least for a years time), and thus the one fire per household per year assumption should hold.

TABLE 1
1985 Fixed/Portable Heater fires (per year) [8]

Type	MISUSE	MECH	CREOSOTE	FUEL ERR.	TOO CLOSE	OTHER DESIGN	OTHER
FIXED,S	3578	534	40050	1388	1282	5554	1015
FP,S	2669	500	17069	1140	751	3947	862
FIXED,G	1193	297	0	0	1753	734	224
PORT,L	1174	912	0	908	635	65	106
PORT,E	1476	1217	0	0	1402	90	116
FIXED,E	774	1174	0	0	1436	155	58
Totals	10864	4634	57119	3436	7259	10545	2381

Row titles on the left: Fixed=fixed heater, Port=portable heater, FP=fireplace, S=solid fueled, G=gas fueled, L=liquid fueled, E=electric.

Accidents involving consumer products are another possible source of information for us, and we have two sources of information [12-13]. Reference 12 gives the number of accidents in 1985 which involved various types of consumer products. These numbers are compiled from hospital emergency room information and the extent of associated injuries is not given. Also, the consumer products "involved" may not be the cause of the accident (See Table 3). However, these values may give us some indication of how often people do "incorrect" things with household consumer products.

As a very gross approximation, we will take the accident statistics in the table which involve products being "in the wrong place at the wrong time" but which didn't actively cause the accident (i.e., passive items such as a toy which one could trip over, but not an active item such as a chain saw which actively

TABLE 2

1985 Heater fires by cause and heater type [8]

Heater Type	Item too close	Installed too close	Creosote	Construction deficiency	Fueling Error
Solid fueled, fixed area	1282	3044	40050	1175	1388
Solid fueled fireplaces	751	1418	17069	2029	1140
Solid fueled chimneys	540	2196	19980	1764	6012
Solid fueled chimney connectors	328	1722	3141	722	164
Liquid fueled portable	635	0	0	0	908
Electric portable	1402	0	0	0	0
Electric fixed area	1436	0	0	0	0
Gas fueled fixed area	1753	381	0	0	0
Gas fueled central heaters	1106	198	0	0	0
Liquid fueled central heaters	181	0	0	0	191
Electric central heaters	104	0	0	0	0
Totals by Ignition Factor	9517	8958	80240	5690	9804

	Usage Error	Other	Other Design	Other Mechanical	Part Failure
Solid fueled, fixed area	3578	1015	1335	534	0
Solid fueled fireplaces	2669	862	500	500	0
Solid fueled chimneys	2664	900	1332	612	0
Solid fueled chimney connectors	730	271	754	369	0
Liquid fueled portable	1102	106	65	277	635
Electric portable	1200	116	90	215	0
Electric fixed area	598	58	155	389	0
Gas fueled fixed area	1193	224	353	297	0
Gas fueled central heaters	1034	215	264	605	1694
Liquid fueled central heaters	583	69	113	622	2710
Electric central heaters	265	73	88	1617	0
Totals by Ignition Factor	15615	3907	5049	6038	5038

	No Maintenance	Electrical Failure	Overloaded	Total Number of fires
Solid fueled, fixed area	0	0	0	53400
Solid fueled fireplaces	0	0	0	26938
Solid fueled chimneys	0	0	0	36000
Solid fueled chimney connectors	0	0	0	8200
Liquid fueled portable	72	0	0	3800
Electric portable	95	1002	181	4300
Electric fixed area	133	785	43	3596
Gas fueled fixed area	0	0	0	4200
Gas fueled central heaters	385	0	0	5500
Liquid fueled central heaters	431	0	0	4900
Electric central heaters	640	2194	218	5200
Totals by Ignition Factor	1756	3981	442	156035

TABLE 3

Injuries involving consumer products in 1985 [12]

Injuries associated with consumer products

The following list of items found in and around the home was selected from the U.S. Consumer Product Safety Commission's National Electronic Injury Surveillance System (NEISS) for 1985. The NEISS estimates are calculated from a sample of hospitals which are statistically representative of institutions with emergency treatment departments in the U.S. and its territories. Injury totals represent estimates of the number of hospital emergency room-treated cases nationwide associated with the various products. However, product involvement may or may not be the cause of the accident.

Estimated Injuries Related to Selected Consumer Products, 1985

Product	Injuries ^a	Product	Injuries ^a
Home Communication, Entertainment and Hobby Equipment:		Heating, Cooling and Ventilating Equipment:	
Miscellaneous hobby equipment	12,855	Chimneys, fireplaces	14,255
Pet supplies, equipment	14,940	Fans (except stove exhaust fans)	14,743
Sound recording, reproducing equipment	~~33,808~~	Heating stoves, space heaters	41,877
Television sets	~~31,888~~	Pipes, heating and plumbing	28,863
Personal Use Items:		Radiators, all	18,704
Cigarettes, lighters, fuel	20,900	Other	23,781
Clothing, all	94,597	Housewares:	
Grooming devices	22,223	Cookware, pots, pans	29,182
Holders for personal items	13,029	Cutlery, knives, unpowered	~~348,687~~
Jewelry	40,608	Drinking glasses	~~121,961~~
Paper money, coins	25,606	Miscellaneous housewares	49,326
Pencils, pens, other desk supplies	44,400	Scissors	18,357
Razors, shavers, razor blades	39,496	Small kitchen appliances	38,441
Sewing equipment	~~29,253~~	Tableware and accessories	92,279
Other	10,632	Other	7,852
Packaging & Containers, Household:		Home Furnishings, Fixtures and Accessories:	
Cans, other containers	164,403	Bathtub, shower structures	~~120,890~~
Glass bottles, jars	98,343	Beds, mattresses, pillows	~~275,521~~
Paper, cardboard, plastic products	46,584	Carpets, rugs	59,245
Yard and Garden Equipment:		Chairs, sofas, sofa beds	~~274,048~~
Chain saws	~~65,743~~	Desks, cabinets, shelves, racks	~~151,183~~
Hand garden tools	32,855	Electric fixtures, lamps, equipment	42,262
Hatchets, axes	~~22,495~~	Ladders, stools	117,594
Lawn, garden care equipment	38,623	Mirrors, mirror glass	~~19,204~~
Lawn mowers, all types	~~68,884~~	Misc. household covers, fabrics	14,562
Other power lawn equipment	~~11,479~~	Other misc. furniture, accessories	~~11,112~~
Trimmers, small power garden tools	~~11,083~~	Sinks, toilets	~~98,349~~
Other	6,614	Tables, all types	~~262,442~~
Home Workshop Equipment:		Other	19,971
Batteries, all types	16,695	Home Structures and Construction Materials:	
Hoists, lifts, jacks, etc	19,038	Cabinets or door hardware	~~20,868~~
Miscellaneous workshop equipment	31,148	Ceilings, walls, panels (inside)	~~198,009~~
Power home tools, exc. saws	~~27,469~~	Counters, counter tops	~~21,284~~
Power home workshop saws, all	~~64,705~~	Fences	~~109,773~~
Welding, soldering, cutting tools	~~21,521~~	Glass doors, windows, panels	~~210,084~~
Wires, cords, not specified	11,937	Handrails, railings, banisters	~~34,849~~
Workshop manual tools	~~110,267~~	Misc. construction materials	92,941
Other	22,751	Nails, carpet tacks, etc	222,647
Home Maintenance:		Nonglass doors, panels	~~208,012~~
Noncaustic cleaning equip., detergents	16,345	Outside attached structures, materials	11,558
Cleaning agents (except soaps)	38,198	Porches, open side floors, etc	~~78,246~~
Drain, oven cleaners, caustics	10,762	Stairs, ramps, landings, floors	~~1,390,085~~
Miscellaneous household chemicals	17,818	Window, door sills, frames	~~34,581~~
Paints, solvents, lubricants	19,342	Other	~~10,975~~
Other	9,282	Miscellaneous Products:	
General Household Appliances:		Dollies, carts	29,850
Cooking ranges, ovens, etc	44,940	Elevators, other lifts	~~10,627~~
Irons, clothes steamers (not toys)	17,157	Fireworks, flares	10,572
Misc. household appliances	21,523	Gasoline and diesel fuels	22,557
Refrigerators, freezers	~~90,458~~	Nursery equipment	141,625
Washers, dryers	~~20,377~~	Toys	123,104

Source: Consumer Product Safety Commission, National Electronic Injury Surveillance System.

^aEstimated number of product-related injuries in the U.S. and territories which were treated in hospital emergency departments in 1985.

causes the injury). Since the data given does not tell how the accident happened, our assessment will have to be based on our personal knowledge of

household product use. A quick calculation from the table shows the approximately 2.3 million accidents of the type which we are interested in occurred in 1985. This would correspond to $2.3/88 = 2.62 \times 10^{-2}$ accidents of this type per year per household. This number could be considered to be the rate at which people put consumer products in places where they should not and cause accidents. (It is probably quite conservative since the data we are using do not differentiate as to how the accident happened and thus we will be including a lot of accidents which do not conform to our definition.)

Another source of information, Reference 14, provides a different perspective on the problem. Utilizing a random sample of homes across the U.S. throughout 1984, an estimate of the number of fires which occur in residences in the U.S. and are not reported to anyone is derived. The method of sampling for the survey will not be given here, but the definition of a fire which they used is:

"Any incident, large or small, that resulted in flames or smoke, and could have caused damage to life or property if left unchecked."

The estimate of the number of unreported fires given is 25,197,000 which indicates that 3 out of 10 households in the U.S. experienced a fire during the year 1984 ($25.2/86.5 = .30$, where 86.5 is the approximate number of U.S. households in 1984 in millions). These results are rather interesting in that the conclusion that is reached is that since there are only around 650,000 reported home fires per year [15], then 97 percent of all home fires are unreported! $((25)/(25 + .65) \simeq 0.97)$

The survey also breaks down the unreported fires into a number of categories, one of which is heater fires. The number of unreported fires attributed to heating appliances is 615,000 during the year 1984. Of these, 237,000 are attributed to portable electric heaters, 29,000 to wood-fueled fireplaces, and 209,000 to fixed heaters of any fuel type. Also discussed is the result that 44.7 percent of heating appliance fires are due to product failure

and 51.2 percent are due to human carelessness. From our previous discussion of ignition factors and these results, we may conclude that approximately :

$$0.512 \times 475,000 = 243,200$$

unreported heater fires of the type we are interested in occurred in 1984. Note that the numbers presented in [14] are based on small samples for heater fires and are subject to substantial uncertainty.

Utilizing the number of households in the U.S. in 1984 as 86.5 million, we arrive at a frequency of unreported heater fires of $243,200/86,500,000 = 2.8 \times 10^{-3} \text{yr}^{-1}$ per household. This number does not reflect the reported heater fire frequency of approximately 1.0×10^{-4} . The combined reported and unreported frequency is 2.9×10^{-3} . Note that since this number is an estimate of the number of real fires which occurred (reported and unreported), it is not an estimate of the number of chances for a fire to occur (the exposures), but is again a "lower bound" on the number of exposures, although much less well known than the number of reported fires discussed previously.

Thus we have three estimates:

1. 1.0×10^{-4} : This is a lower bound which we know fairly accurately from the number of large fires caused by heaters which are reported every year. It combines "too close" fires and some of "mechanical" fires. The data is from [8].
2. 2.6×10^{-2} : This is a very crudely estimated "upper" value of the exposure frequency derived from accident statistics involving consumer products [12]. This value does include accidents involving heating appliances, space heaters, fireplaces, etc. but only includes those accidents in which an injury occurred. The injuries in the data are also only those which are reported to hospital emergency rooms. However, since the data reflects "consumer misuse of consumer products" for all types of products, we may use it as an indicator of the "number of times people

misuse consumer products”, and since we are looking at a subset of their misuse (putting them too close to a heater, etc.), we may look upon this value as an upper bound to the $fr(exp)$.

3. 3.0×10^{-3} : This is an estimate of the frequency of heater fires in residences in the U.S. It is subject to substantial uncertainty and since it reflects unreported fires from [14], it incorporates many small fires where people “catch it in time” (i.e., after ignition, but before substantial damage may occur).

The next step is to assess a distribution for the frequency of exposure. Since we expect the frequency of exposure to have a relationship to the number of fires which occur, we have several options and will utilize the lognormal distribution. The lognormal distribution places greater probability on the lower portion of the assessed distribution, while still giving credence to upper tail values. In fact, we must be careful that the upper tail values do not control the distribution characteristics. In our case, since the frequency of fires derived from reported fires is a reasonably well known number and the number of exposures can not be less than the number of fires which actually occurred, we may use the $1.0 \times 10^{-4} yr^{-1}$ value as a lower percentile of the distribution. To assess a second value to characterize the distribution, we might:

1. Utilize the consumer product accident frequency of $2.6 \times 10^{-2} yr^{-1}$ per household as an upper percentile of the distribution since it is a rather poorly known value and is probably on the high side since it is derived from many types of accidents.
2. Utilize the reported plus unreported heater fire estimate as a measure of central tendency since it is probably much closer to the number of exposures which really occur than the reported fire number is. Since the uncertainty is substantial, yet the estimate is of the number of fires which occurred as opposed to the number of exposures which may have

resulted in fire (which must necessarily be higher), we will use this estimate as a median indicator of the exposure frequency.

If we utilize the first assumption and assess a distribution assuming that the first percentile is 1.0×10^{-4} and that the 99th percentile is 2.6×10^{-2} , we get the distribution shown in Figure 8. If we utilize the first percentile as 1.0×10^{-4} and the median as 3.0×10^{-3} , we get the distribution shown in Figure 9.

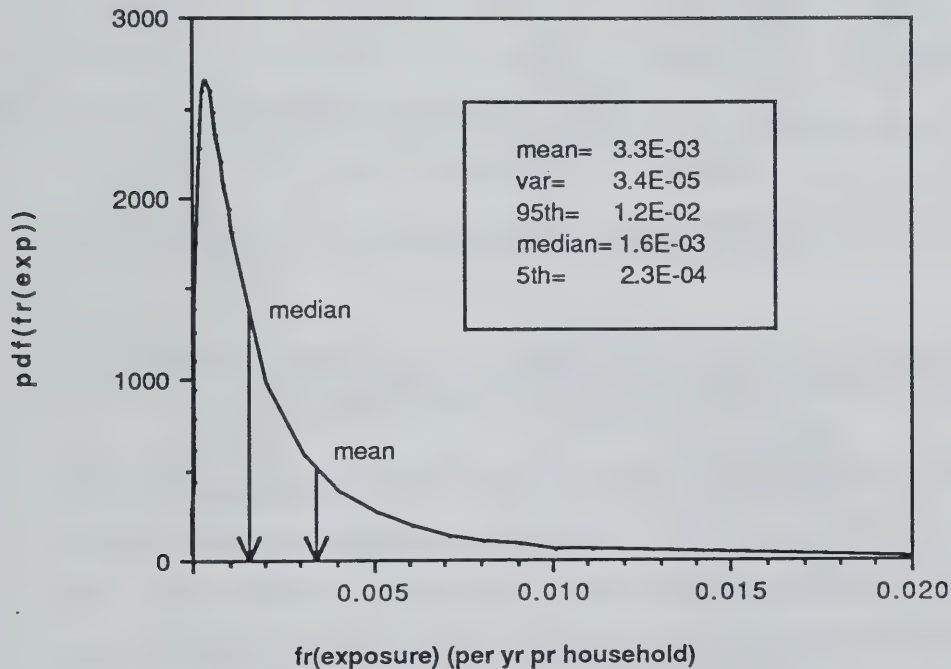


Figure 8: Example Lognormal distribution for $fr(exp)$ utilizing 1.0×10^{-4} as the 1st percentile and 2.6×10^{-2} as the 99th percentile.

2.2 DISCUSSION

We must now choose which distribution to use to characterize our state of knowledge. Figure 8 shows a distribution which reflects that the consumer accident frequency which we have calculated is probably high, since it includes

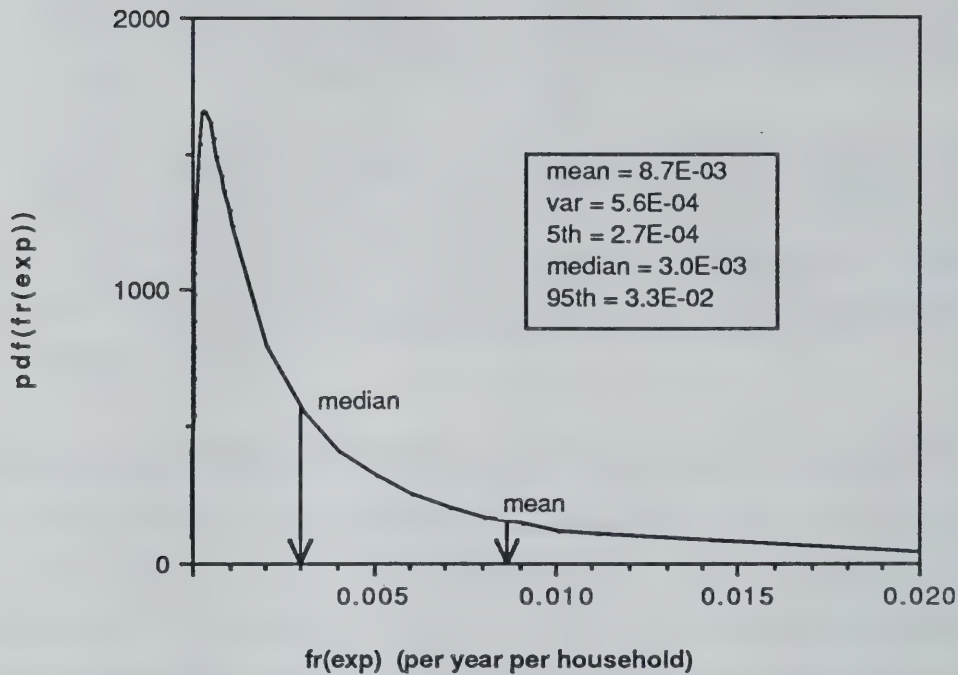


Figure 9: Example Lognormal distribution for $fr(exp)$ utilizing 1.0×10^{-4} as the 1st percentile and 3.0×10^{-3} as the median.

many different types of accidents (it is supposed to reflect the number of times “people do incorrect things with consumer products”, and thus should implicitly include all fire incidents, whether reported or not) and thus is the 99th percentile. We also see that the mean and the median bracket the value of the unreported fire incidents and that the reported fires number is utilized as a “lower bound” (i.e. 1st percentile).

The distribution in Figure 9, utilizing only the two values which are from fire statistics, gives a 95th percentile value which is already higher than the consumer product accident frequency. Since we consider this number to already be something of an upper bound, this distribution does not reflect our state-of-knowledge.

Thus, since the distribution in Figure 8 reflects well both the lower and upper values we have derived, and also places the unreported fires value in a central position (which is reasonable since it must necessarily be lower than the total number of exposures by our definition, and also greater than the reported number of fires, but is somewhat uncertain in value), we choose this distribution to reflect our state-of-knowledge of the frequency with which consumer products are exposed to alternative heating devices. The definition of "exposure" is that the product and the heater must appear together in such a way that ignition of the product is possible. How this occurs was discussed briefly in Section I and will be elaborated on in Section 4.3. Characteristic values from the distribution of $fr(exp)$ are given in Table 4.

TABLE 4

State-of-Knowledge Distribution of $fr(exp)$ (per year per household)

LOGNORMAL DISTRIBUTION		
MEAN	=	3.3E-03
VARIANCE	=	3.4E-05
95TH PERCENTILE	=	1.2E-02
MEDIAN	=	1.6E-03
5TH PERCENTILE	=	2.3E-04

Some discussion of the meaning of this distribution is required. In this work, we are looking at the population of residences in the U.S. as a generic class without regard to such things as the physical location of any given residence. This reflects the objective of the overall methodology to assess the change in risk to the U.S. public from a change in a consumer product. This method could, however, be applied to a specific dwelling, in which case the assessed $fr(exp)$ distribution given above may not be applicable. This is caused by the fact that the fire statistics used to derive the distribution do not reflect

the regional differences in fire frequencies (which are important for heater fires [11]). In later sections of this work, this same type of discussion will apply, i.e., when we talk about the probabilities of a specific heater type being present as an igniter, the generic probabilities we derive will be for the population of U.S. residences, but if we were analyzing a specific dwelling, some of the probabilities might even be 0.0! (e.g., if the dwelling did not have a wood stove, the probability of a wood stove being the ignitor would be 0.0) We are not, however, considering this type of effect.

Another point which needs to be made is that this distribution is for consumer products as a general class, since the statistics used to form it were for fires in which any type of material was ignited. One could restrict the statistics to specific heater types or specific types of material first ignited to achieve a distribution which is applicable to that specific combination of igniter and product. However, then the unreported fire and the consumer product accident frequency would not have been useful, since the specific ignitor/target information is only available from the reported fire data bases.

III

PHYSICAL DESCRIPTION OF THE HEATER/TARGET INTERACTION

To calculate the second factor in Equation 2, the frequency of ignition of the target given exposure to a heater, we must be able to physically describe the thermal environment to which the target is exposed as well as the thermal response of that target. To characterize the thermal environment seen by the target, we must be able to describe the thermal output of the heater (or heaters) which we are considering as ignition sources. The response of the target will then be governed by physical characteristics of the target material itself.

3.1 MODEL OF THE HEATER THERMAL OUTPUT

Several types of heaters may be described grossly as rectangular radiating areas (flat electric heaters, baseboard heaters, fireplaces) or radiating cylinders (kerosene heater, wood stove, See Figure 3). If we take these surfaces to be described as isothermal and diffuse radiators, and in addition, specify the radiant output of the surface, we may describe the radiation field in front of the radiator fairly easily.

The major difficulty in calculating the heat flux at an arbitrarily oriented point in space in front of a surface lies in calculating the view factor to the point. The approach utilized in this work involves restricting the geometry of the radiator/target system so that analytical solutions to the viewfactor equations are possible. The major restrictions are:

1. The radiator must be rectangular or cylindrical.

2. The target is modeled as a rectangular slice of a solid.

- For the rectangular radiator, the target must be oriented in a plane which is perpendicular to the radiator's plane and parallel to one of the radiator's axes (see Figure 10).
- For the cylindrical radiator, the target must be oriented with its front edge parallel to the cylinder axis (see Figure 10).

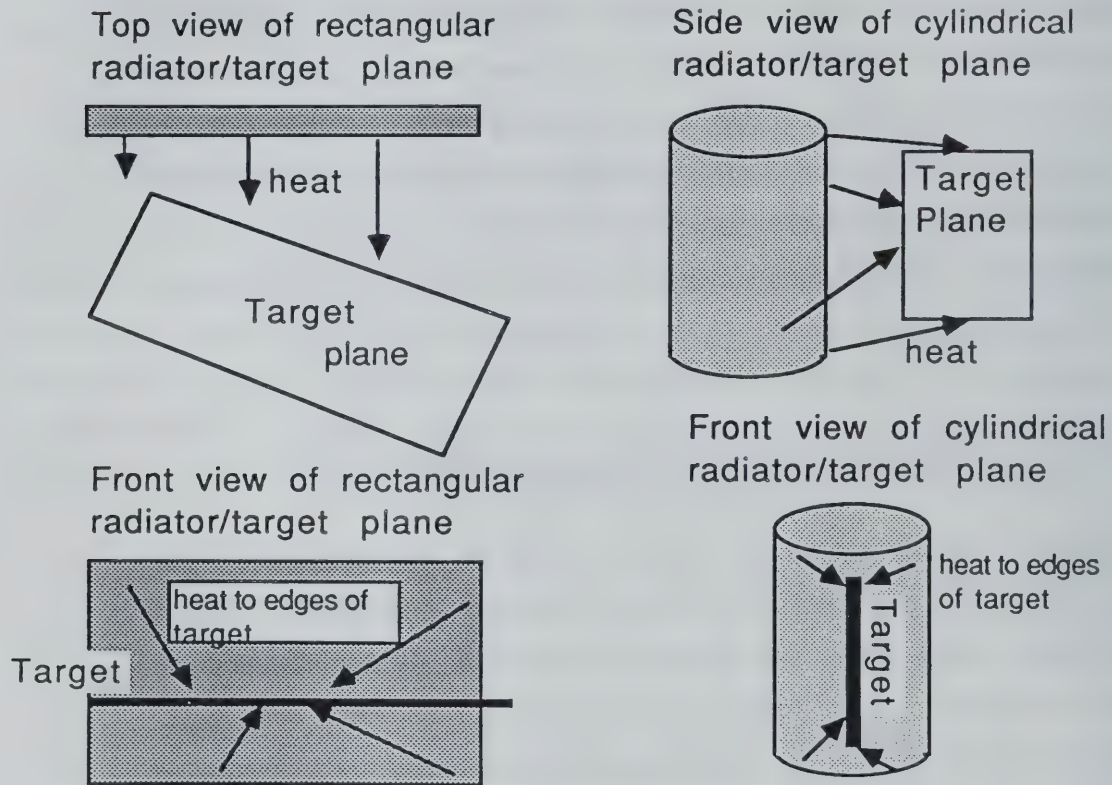


Figure 10: Geometry for the rectangular and cylindrical radiators.

These restrictions were chosen to allow the modeling of a variety of items which might be found in a residence and exposed to a heater (such as cushions on upholstered furniture, see Figure 4). The target material is modeled as an inert homogeneous two-dimensional slab with constant thermal properties.

The physical calculations (view factor calculations, heat flux calculations, temperature rise of the target, etc., described in Sections 3.1.1 through 3.1.3) are performed by a computer code written in Fortran. The user inputs the location and size of the radiator as well as its thermal output, and then the location and thermal properties of the target. From this input, the code calculates the portion of the radiator which each side of the target can see (Section 3.1.1), then calculates the viewfactor to each point on the surface of the target (Section 3.1.2), and then the heat flux to each point (in W/m²). This point-wise heat flux is then utilized in the target temperature calculations to calculate the time-dependent temperature rise in the target slab. This temperature calculation includes radiative and convective heat losses from the boundaries of the target to the rest of the room (which is assumed to be at a uniform ambient temperature which can be specified by the user, Section 3.1.3).

3.1.1 *Portion of the Radiator Seen by Sides of the Target*

For a rectangular target being irradiated by a rectangular or cylindrical radiator, each side of the target can see anywhere from all of the radiator to none of it. As can be seen in Figure 11, we must calculate the amount of the radiator's length or height which can be seen by each side of the target. Figure 11 shows that for the rectangular radiator, side 1 sees part of the radiator, sides 2 and 3 see none of it, and side 4 sees all of it. Thus, sides 2 and 3 will see no heat flux, side 4 will see the entire flux from the radiator, and side one will only see an effective radiator of length L_{eff1} . This means that side 1 will be exposed to a heater power of only

$$P_{side1} = P_{radiator} \frac{L_{eff1}}{L_{radiator}}$$

Similarly, Figure 12 shows the situation for a cylindrical radiator. These effective lengths are used to calculate the viewfactors to the points on the surface of the target where the incident heat flux needs to be calculated.

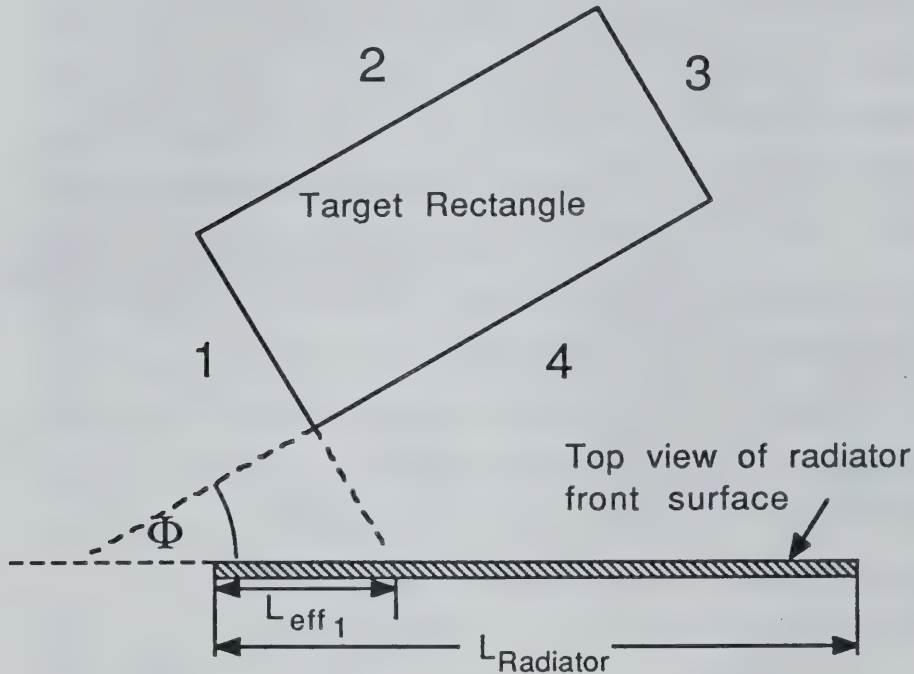


Figure 11: Portion of the Rectangular Radiator Seen by the Target Sides.

3.1.2 Viewfactor Calculations

The calculation of the viewfactor from a rectangle to a differential element in space in front of that rectangle is simple when the element is oriented either in a plane which is parallel or perpendicular to the rectangle. Analytic solutions exist for these cases and some simple viewfactor arithmetic is all that is necessary to calculate almost any configuration of this type. For our purposes, we do not want to limit the geometry to only parallel and perpendicular orientations, therefore we can not utilize the cataloged viewfactor expressions.

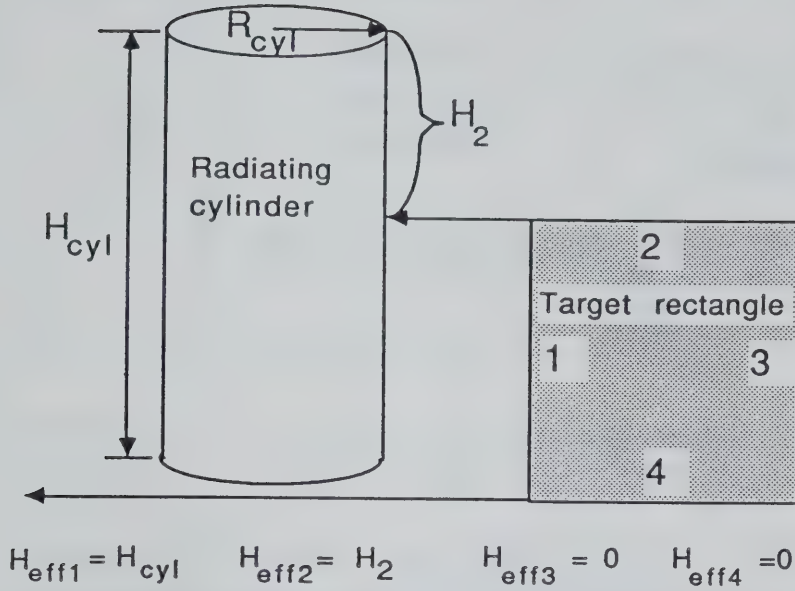


Figure 12: Portion of the Cylindrical Radiator Seen by the Target Sides.

The general expression for a viewfactor from a surface i to a surface j is given in Equation 6:

$$F_{ij} = \frac{1}{A_i} \int_{A_i} \int_{A_j} \frac{\cos \Theta_i \cos \Theta_j}{\pi R^2} dA_i dA_j \quad (6)$$

where R is the distance between elements on the surfaces and the angles are related to the geometrical arrangement of the surfaces. This integral involves the integration over both of the surface areas (or over one surface for the viewfactor from a differential element to a surface). Since we need the viewfactor at a large number of points, it is not feasible to numerically evaluate an area integral for every point. However, since we have restricted our geometry to a simple one except for the angle Φ between the target side and the radiator (see Figures 11 and 13), we can utilize a transformation of the

surface integral into two contour integrals as outlined in Reference 16. This transformation gives us:

$$F_{d1-2} = \frac{\cos(90 - \Phi)}{2\pi} \int_{C_2} \frac{-z_1 dy_2}{S^2} + \frac{\cos(180 - \Phi)}{2\pi} \int_{C_2} \frac{(y_2 - y_1)dx_2 - (x_2 - x_1)dy_2}{S^2} \quad (7)$$

where

$$S = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2}$$

The coordinate system is given in Figure 13. Since our surfaces are rectangular and the normal to the differential element is set up parallel to the x axis, the contour integrals can be solved analytically and result in a complex, but analytic solution for the viewfactor from a differential element to the radiating rectangle. (See Appendix A.) The only assumption we now make is that the viewfactor will be constant in a 1 cm square area centered on the differential element, and then we can use reciprocity to calculate the viewfactor from the radiating rectangle to the "point" in space we need. If the radiating rectangle is surface 2 and the one cm square "differential element" is surface 1, reciprocity gives us:

$$A_2 F_{21} = A_1 F_{12}$$

and thus:

$$F_{21} = \frac{A_1 F_{12}}{A_2} \quad (8)$$

Thus, F_{21} can be calculated since our viewfactor calculation gives us F_{12} (within the 1 cm² approximation), A_2 is the area of the radiator, and A_1 is 1 cm² (or 0.0001 m²).

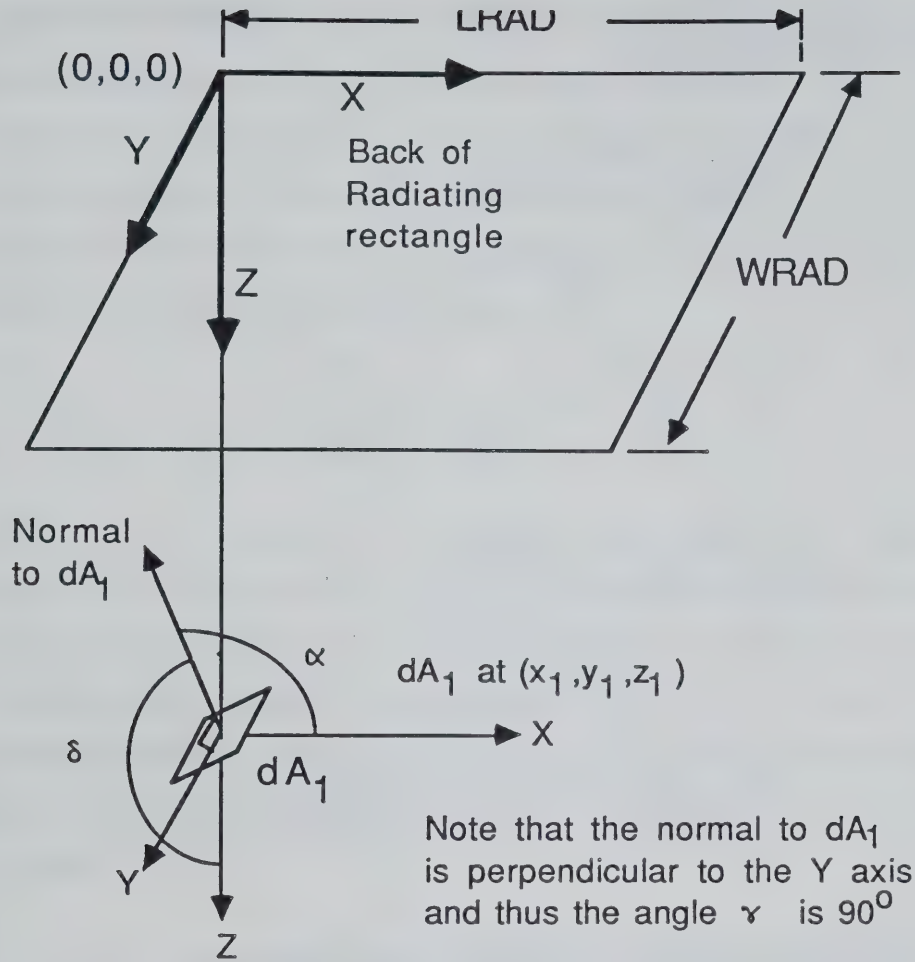


Figure 13: Geometry of the viewfactor contour integration.

We will be much more restrictive on the geometry for the cylindrical radiator, since no such simple analytic solution to the viewfactor equations is possible for a cylinder to an arbitrarily oriented differential element. To calculate the viewfactor from a radiating cylinder to an element which is oriented as shown in Figure 14 (e.g. at the base of the cylinder with the plane of the element either parallel or perpendicular to the cylinder axis), we may use well known analytic results for these viewfactors as given in Equations 9 (parallel) [16-17] and 10 (perpendicular) [18]. Equation 10 is actually a

limiting case for the viewfactor to a truncated cone from a differential element perpendicular to the cylinder axis.

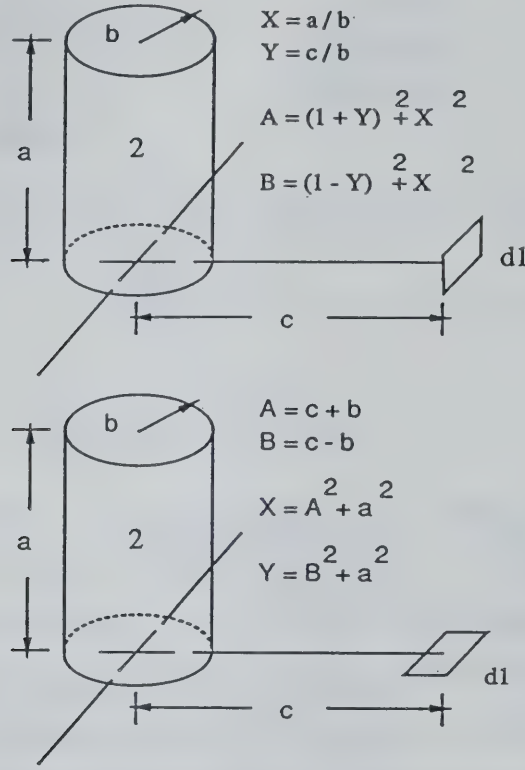


Figure 14: Cylindrical radiator to differential element geometries.

$$F_{d1-2} = \frac{1}{\pi Y} \tan^{-1} \left(\frac{X}{\sqrt{Y^2 - 1}} \right) +$$

$$\frac{X}{\pi} \left[\frac{A - 2Y}{Y\sqrt{AB}} \tan^{-1} \sqrt{\frac{A(Y-1)}{B(Y+1)}} - \frac{1}{Y} \tan^{-1} \sqrt{\frac{Y-1}{Y+1}} \right] \quad (9)$$

$$F_{d1-2} = \frac{1}{\pi} \left[\tan^{-1} \sqrt{\frac{A}{B}} - \frac{AB + a^2}{\sqrt{XY}} \tan^{-1} \sqrt{\frac{XB}{YA}} \right] \quad (10)$$

The only difficulty now is when the element is located higher or lower than the ends of the cylinder or at a point between the ends. However, by knowing the parts of the cylinder which each side can see (Section 3.1.1), and thus the parts

which each element on those sides can see, we may use viewfactor algebra to break the problem down into parts which can be solved with the analytic equations 9 and 10. The assumption that the viewfactor is constant in a 1 cm^2 area around the element is still used and the calculation of the viewfactor from the cylinder to the differential element proceeds identically to that for the rectangular radiator case using Equation 8.

3.1.2.1 Accuracy of the Calculated Viewfactors

The accuracy of the calculated viewfactors will be established by comparing special cases for which the viewfactor is known and simple (perpendicular and parallel orientation) with the code results, and then verifying that the code results are physically reasonable and continuous between these extremes. For the cylindrical viewfactor case, the results are derived purely from analytic solutions and must necessarily be accurate (to machine precision) if they are coded correctly.

For the rectangular radiator case, however, the results stem from our solution of the contour integrals and should be checked. Simple analytical results for the geometries shown in Figure 15 are given as equations 11 and 12:

$$F_{d1-2} = \frac{1}{2\pi} \left(\frac{X}{\sqrt{1+X^2}} \tan^{-1} \left(\frac{Y}{\sqrt{1+X^2}} \right) + \frac{Y}{\sqrt{1+Y^2}} \tan^{-1} \left(\frac{X}{\sqrt{1+Y^2}} \right) \right) \quad (11)$$

$$F_{d1-2} = \frac{1}{2\pi} \left(\tan^{-1} \left(\frac{1}{Y} \right) - \frac{Y}{\sqrt{X^2+Y^2}} \tan^{-1} \left(\frac{1}{\sqrt{X^2+Y^2}} \right) \right) \quad (12)$$

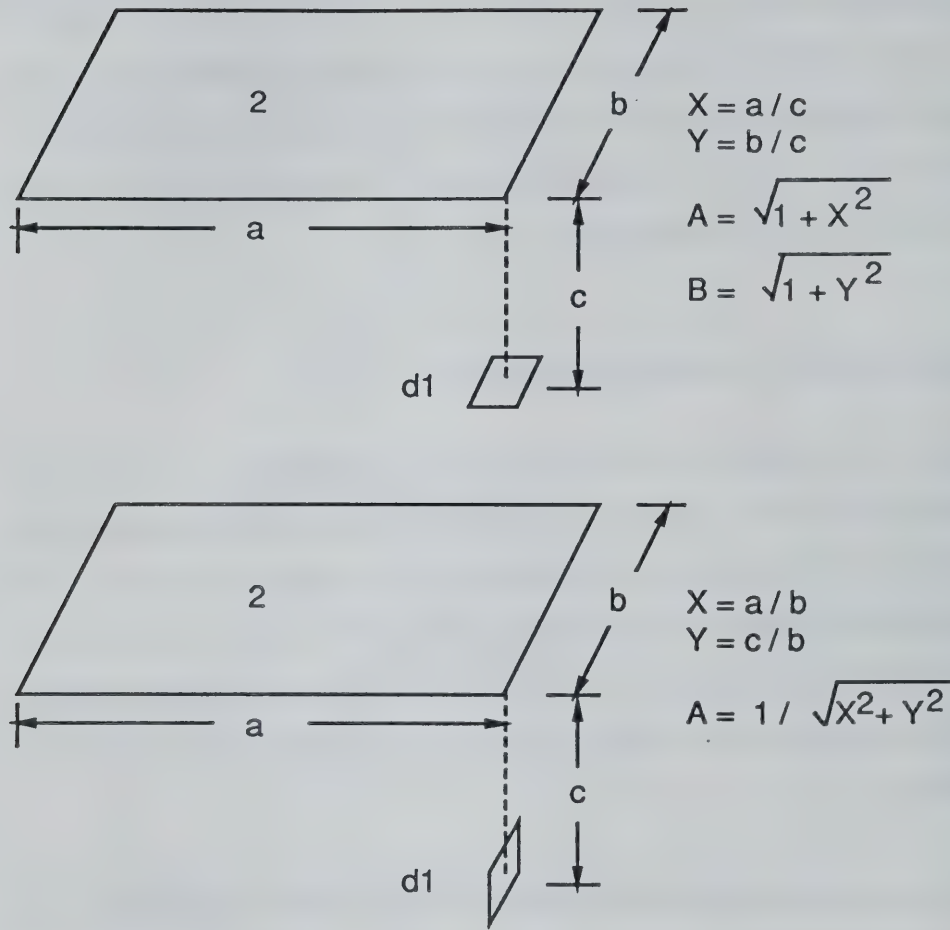


Figure 15: Rectangular geometries for which simple viewfactors are available.

Thus if we choose an arbitrary test case with $a=0.6\text{m}$, $b=0.5\text{m}$, and $c=0.2\text{m}$, $F_{d1-2} = 0.225$ for the parallel orientation and $F_{d1-2} = 0.158$ for the perpendicular case from the analytic solutions. Using the code and placing a small surface at the corner of the radiator, we obtain 0.225 for the parallel case and 0.158 for the perpendicular. A graph of F_{d1-2} generated from the code as the angle is varied from 0 to 90 degrees is shown in Figure 16. We have no

analytic results with which to compare these results between 0 and 90 degrees. However, the graph shows a physically reasonable trend.

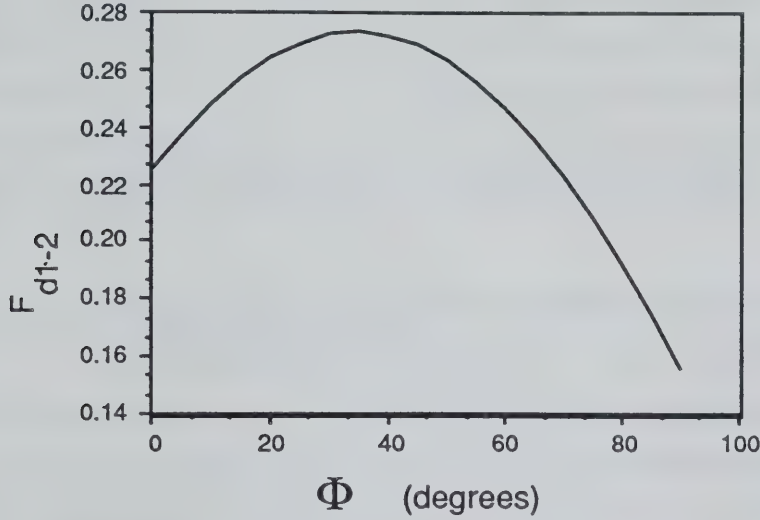


Figure 16: Viewfactor from a differential element to a rectangular radiator with the element located 0.2 m from the radiator's corner and its orientation varying from 0 to 90 degrees (parallel to perpendicular.)

3.1.3 Heat Transfer at the Target

The heat transfer to, from and within the target solid is calculated by the code using standard conduction, convective, and radiative heat transfer relations shown as equations 13-15, numerically evaluated using an implicit finite difference scheme solved by iteration.

$$\frac{1}{\alpha} \frac{\partial T_S}{\partial t} = \frac{\partial^2 T_S}{\partial x^2} + \frac{\partial^2 T_S}{\partial y^2} \quad (13)$$

with boundary conditions:

$$T_S(x, y, 0) = T_{env} \quad (14)$$

at time = 0.0, and along the four sides of the rectangular target:

$$-k \left(\frac{\partial T_S}{\partial x} + \frac{\partial T_S}{\partial y} \right) = h(T_{env} - T_S) + \varepsilon q_{ext} - F_{12} \sigma \varepsilon T_S^4 + (1 - F_{12}) \varepsilon \sigma (T_{env}^4 - T_S^4) \quad (15)$$

- T_S = time and space dependent solid temperature (target) (K)
- T_{env} = temperature of the environment around the target (K)
- ε = material surface emissivity
- σ = Stefan-Boltzmann constant: $5.667 \times 10^{-8} (\text{W/m}^2 \text{K}^4)$
- F_{12} is the viewfactor from a point on the target to the radiator
- k = thermal conductivity of the target material (W/mK)
- α = thermal diffusivity = $k/\rho c_p$, where ρ is the density (kg/m^3) and c_p is the specific heat (J/kg K) of the target material
- q_{ext} = external heat flux from the heater at a point on the target (W/ m^2)

The terms in Equations 13-15 have the following interpretations:

- $\frac{1}{\alpha} \frac{\partial T_S}{\partial t}$ is the change in the target temperature with time.
- $\frac{\partial T_S}{\partial x} + \frac{\partial T_S}{\partial y}$ drive the conduction heat transfer within the target solid (i.e., are the change in temperature with position in the x and y directions.)
- $h(T_{env} - T_S)$ is the convective heat loss/gain from the target's surface.
- εq_{ext} is the external radiative heat flux which is absorbed at the surface of the target (assuming that the grey body approximation holds and the emissivity is equal to the absorptivity.)

- $F_{12}\sigma\epsilon T_S^4$ is the portion of the reradiated heat from the target which is reradiated back to the heater.
- $(1 - F_{12}) \epsilon\sigma(T_{env}^4 - T_S^4)$ is the radiative heat loss to the target's surroundings, which are taken to be at a uniform temperature T_{env} . The viewfactor F_{12} "subtracts" that part of the radiative loss which has already been accounted for in the radiative loss back to the heater.

The results from the temperature calculations give the temperature at many points within and on the surface of the solid as a function of time.

3.2 SIMULATION OF EXPERIMENTS

Implicit in the design of the code is the necessity of using a temperature or heat flux based ignition criteria to predict the ignition of the target solid, since all other ignition aspects, such as the chemical kinetics of the problem have been ignored. The code essentially consists of two pieces: the first part calculates the viewfactors and heat fluxes from the heater to the target solid and then the second part takes these values and calculates the resultant temperature rise in the solid.

Unfortunately, while there have been many different types of ignition experiments performed on a wide variety of materials, there are no results which we can simulate directly with the code. Most experiments utilize apparatus which are designed to provide uniform heat fluxes on a target and use cone-shaped or other heater geometries. An example of this is Reference 19 in which the ignition times and temperatures of several different thermoplastics are studied.

The code is fairly modular and the temperature calculation routines can be separated from the heat flux calculations, so it is decided to test the temperature response portion of the code separately. All we need to do is to input a flux distribution (and a few other parameters) to the temperature

calculation routines in place of the calculations which the code would normally perform. For our purposes, this flux distribution will be uniform along one side of a thin thermoplastic target as described in the next section.

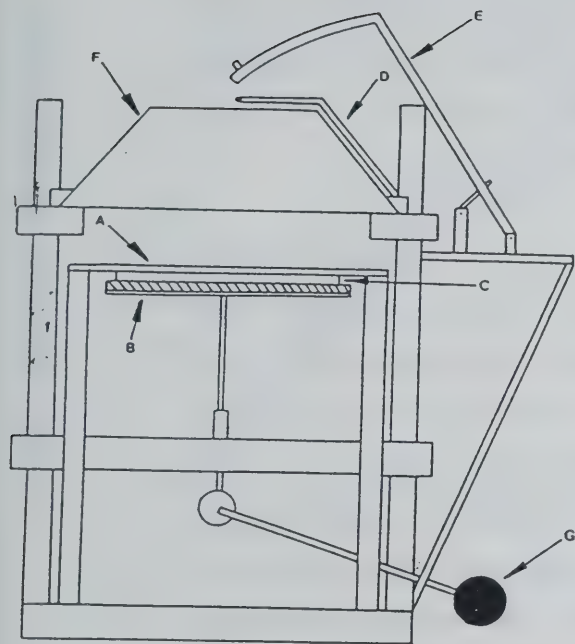
3.2.1 *Temperature Response Simulations*

The experiments in Reference 19 consist of applying a constant heat flux to one surface of a 6mm thick piece of thermoplastic and measuring the front and rear surface temperatures until the material ignites. The rear surface is insulated (See Figure 17). For our simulations we will choose one of the six plastics tested, black Perspex, and will take the thermal properties as stated by the manufacturers (See Table 5). This leaves only the surface emissivity to evaluate. A discussion of the material emissivity is given in [19] and for the material which we have chosen to simulate, the value varies from 0.70 to 0.90 depending upon the heater temperature. Since our model does not take into account the spectrum of the heater, we will use this range as upper and lower bounds with 0.8 as the most likely value and investigate the effects.

TABLE 5

Perspex Thermal Properties (provided by the manufacturer)

Imperial Chemical Industries (ICI), Perspex 962: cast acrylic sheet, black.
Thermal conductivity = 0.19 W/mK
Specific heat = 1500 J/kg K
density = 1190 kg/m ³



Schematic diagram of the ISO ignitability apparatus: A, top plate; B, supalux backing board; C, sample; D, stationary pilot; E, "nodding duck" pilot; F, conical heater; G, counterweight.

Figure 17: Experimental Geometry [19]

The experimental heat fluxes as measured range from 10 to 50 kW/m² . However, the authors in [19] tell us that these measured values are 10 percent too high and since they use the lowered values in their calculations, so will we. The actual fluxes then range from 9 to 45 kW/m².

As can be seen in Figures 18-21, the experimental ignition times are well duplicated by our code for the higher heat fluxes (18 - 45 kW/m²), and it is somewhat conservative at the lower flux levels. The experimental ignition time and temperature ranges given on the plots correspond to $\pm\sigma$ (one standard deviation) from the mean of a sample of five replicate ignition tests at each incident heat flux value. The results of the code calculations can be seen to be more spread out over the 0.7 to 0.9 emissivity range (the outside bounds of

the range we consider to be possible) than the experimental results. If we consider the central value ($\varepsilon = 0.8$) which we consider the most probable value in the range and the code predictions using this value, we see that the ranges are much narrower and close to the experimental ranges. They do, however, follow the same pattern of getting more conservative at the lower heat fluxes for the thin samples used in these experiments.

The conservatism in the lower heat flux range can be explained by noting that our code, when an insulated surface is specified, allows no heat loss from the surface, while in reality, there is heat lost through the insulated back face. While investigating the concept of a critical heat flux for ignition, the authors of Reference 19 varied the insulating material used to insulate the back face of the thermoplastic slab (only two different materials) and found that the more effective the insulating material was, the quicker the material ignited when the heat flux was low (near the "critical" value). This would indicate that heat losses from the rear face of the slab are important when the duration of the experiment is long compared to the thermal penetration time of the slab. Thus, our code would tend to predict a faster temperature rise in the solid than would actually happen when the heating rate is low enough so that the back face heats up substantially.

3.2.2 *Summary of Sections II and III*

In Sections II and III, we have developed a distribution for the frequency of exposure of consumer products to alternative heating appliances and have described a physical model for the heat transfer to, and ignition of those products. The distribution of $fr(exp)$ which we have derived is based on data from known (reported) fires which have involved alternative heating devices, from an estimate of the number of unreported fires which have involved alternative heating devices, and from statistics for the involvement of consumer products in accidents. For the known fire incidents and the consumer product

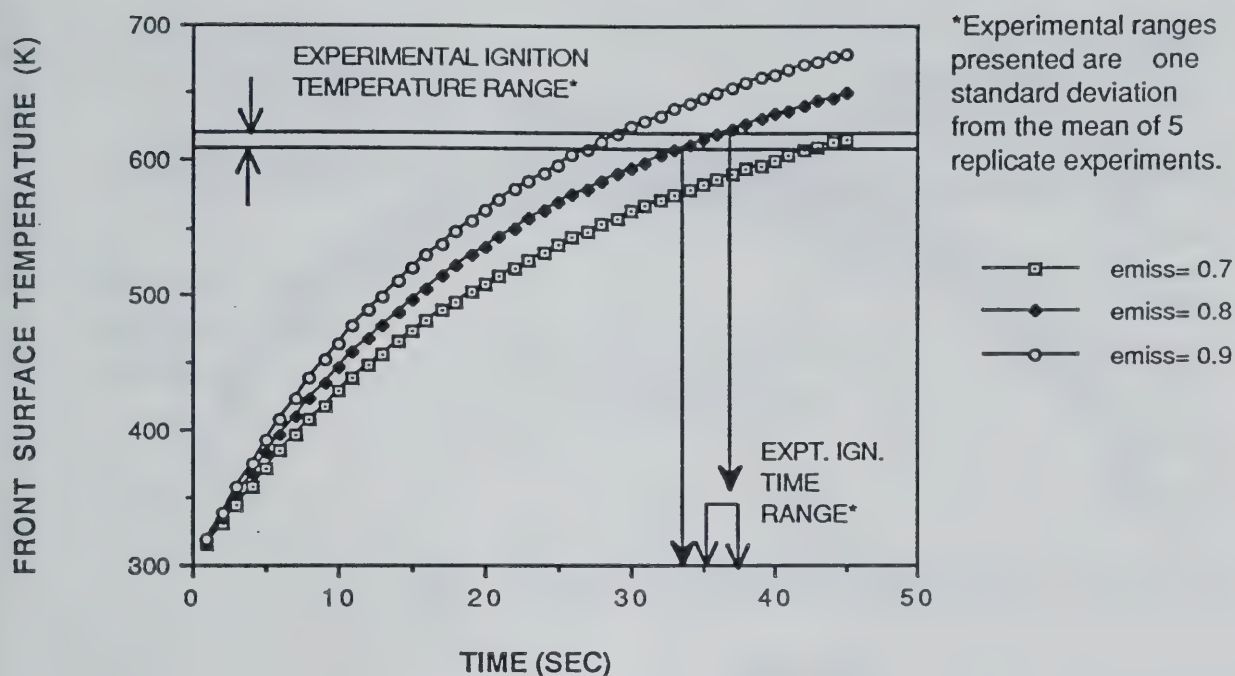


Figure 18: Surface Temperature vs. time for PX slab at 45kW/m^2 incident heat flux

accidents, we have tailored the use of the data to describe only the exposure incidents which involve consumer products in the home (as opposed to structural materials) and those consumer product accidents which are most likely to have been caused by careless placement of a product (as opposed to a product such as a chain saw which is more likely to have actively participated in the accident!).

The model for the heat transfer between the heater and the consumer product and the subsequent ignition of that product is restricted to rectangular and cylindrical heaters and a two-dimensional rectangular target object. Within these restrictions, however, many types of alternative heating appliances may be described and the two-dimensional rectangular target object may be used to model a "slice" of many different types of objects.

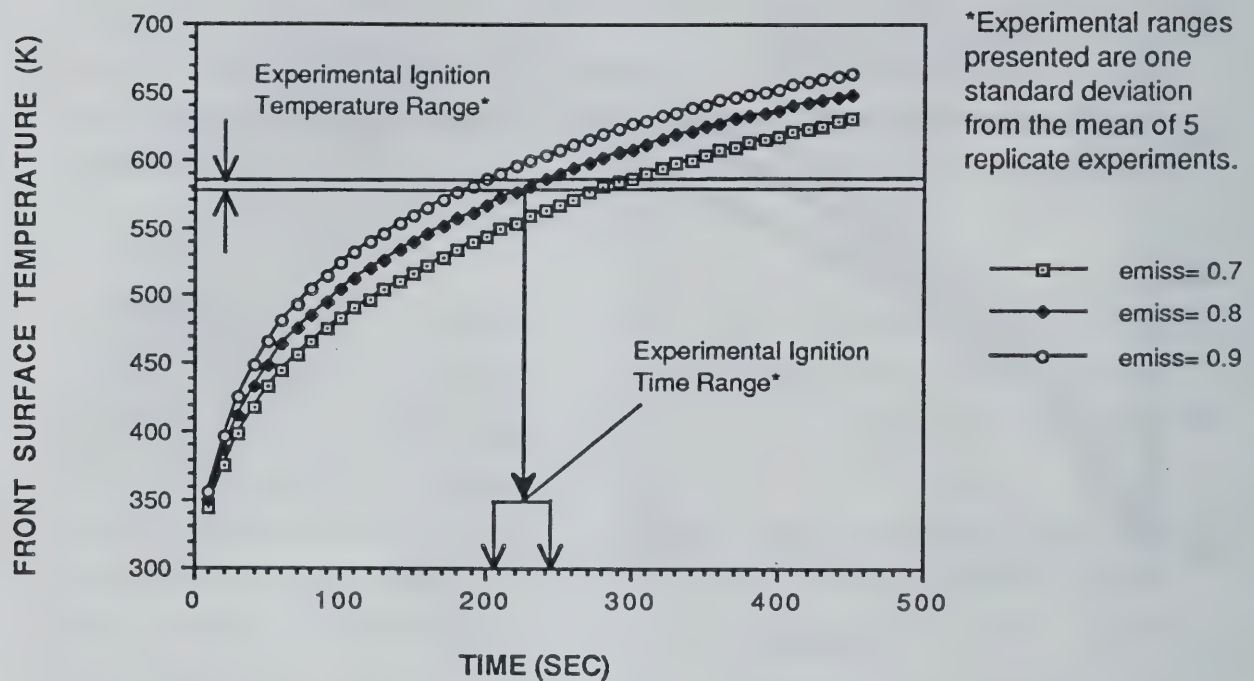
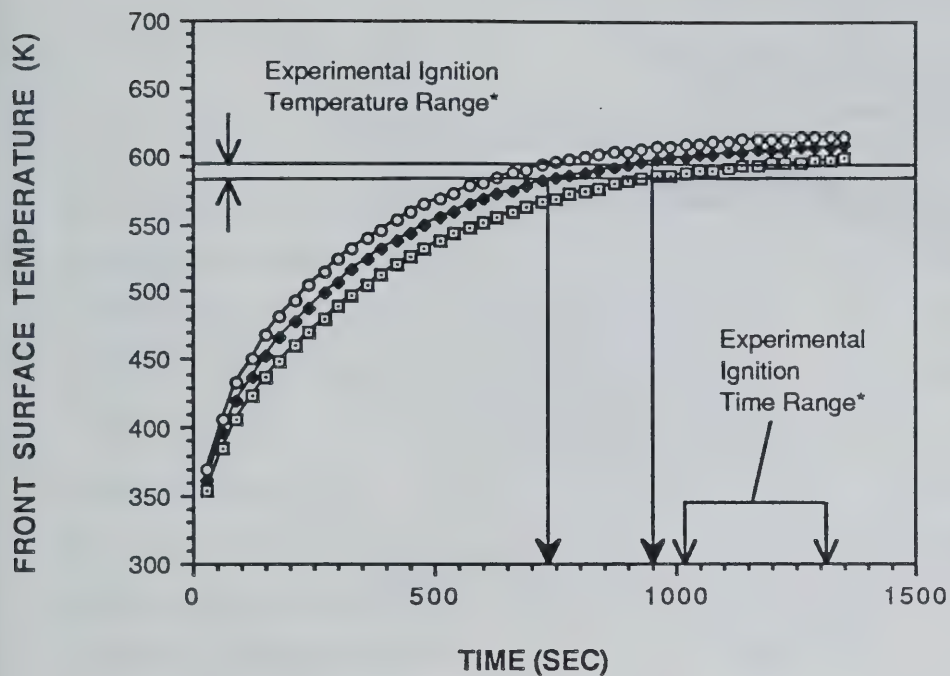


Figure 19: Surface Temperature vs. time for PX slab at 18kW/m^2 incident heat flux

Thus, we now have the first term of Equation 2 ($f_r(\text{exp})$) and a model for the physical estimation of the second term ($f(\text{ign}|\text{exp})$). We must now describe the physical and probabilistic processes which occur during an ignition scenario, as well as the uncertainties in these processes. This is the subject of Section III.



*Experimental ranges presented are one standard deviation from the mean of 5 replicate experiments.

Figure 20: Surface Temperature vs. time for PX slab at 11kW/m^2 incident heat flux

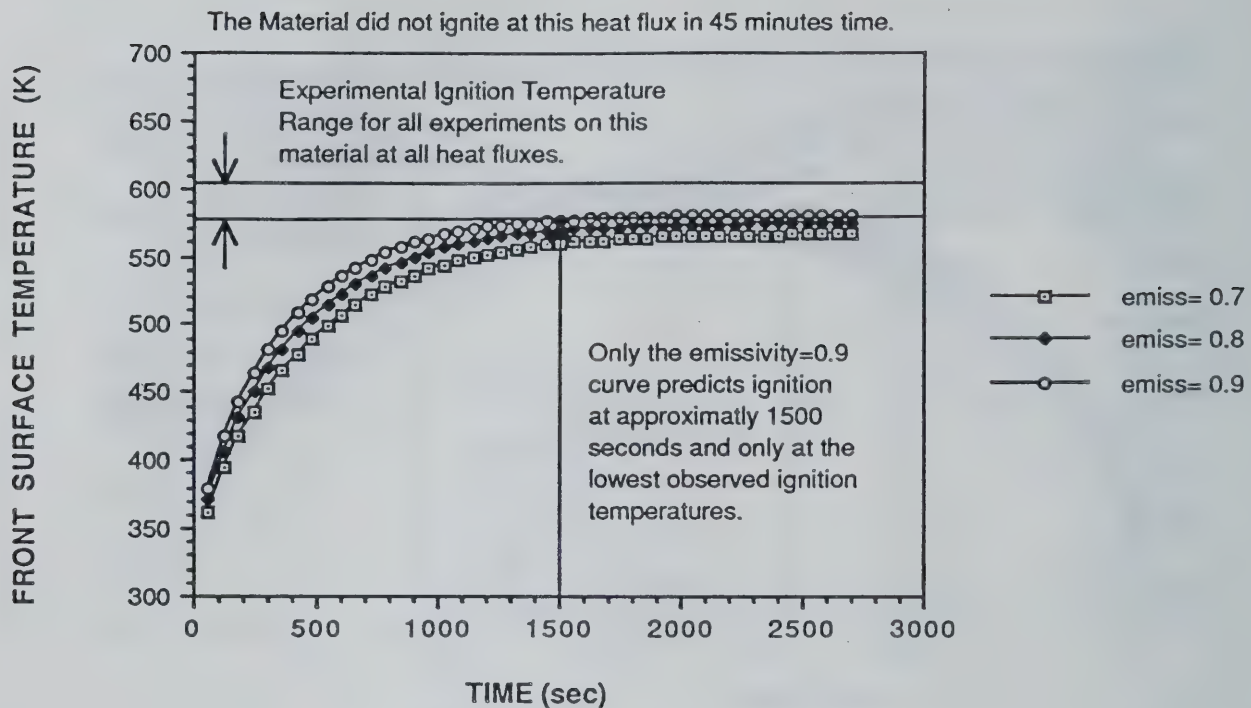


Figure 21: Surface Temperature vs. time for PX slab at 9 kW/m^2 incident heat flux

IV

RESIDENTIAL IGNITION SCENARIO

So far, we have outlined the physical calculations which must be performed, along with two of the major probabilistic factors which are necessary in the calculation of the ignition frequency of a material. These discussions have been general in nature except for the derivation of a distribution for $fr(exp)$ which is specific to radiative exposure from alternative heating devices, and the code verification using a specific thermoplastic ignition experiment. The usual use of this method, however, will be to analyze the ignition frequency for a specific new material. To show the method in practice, we now need to choose a specific material to analyze.

As discussed during the derivation of the $fr(exp)$ distribution, we are interested in the radiant ignition of consumer products in residential buildings. A typical radiant ignition scenario involving alternative heating devices and consumer products is the ignition of upholstered furniture. This class of objects involves the ignition of some type of fabric. Therefore, the product which we will analyze will be a fabric.

Generally, the method will be used to analyze some new product for which little, or more likely no, historical fire data is available (if the product has been around long enough to generate a reasonable amount of data on its performance, it is really not a "new" product). We will need to develop a set of fabric properties to use which will correspond to a class of materials for which data is available (note that the properties of the single material under analysis would normally be used).

A reasonable way to choose a class of materials is to utilize an existing classification scheme such as that for the National Fire Incident Reporting System [4]. Here fire incidents are broken down into a large number of factors such as the ignition source, the form of the first item ignited, the type of material ignited, as well as many other factors pertinent to the fire scenario. An existing classification under category "Type of Material Ignited", and class "Fabric, Textile, Fur," is a subclass defined as:

"Cotton, rayon, cotton fabric, finished goods. Included are canvases and all polyester-cotton blends."

This is the class of fabric which we will analyze.

We will also need to make some modeling assumptions when we do the heat transfer calculations since the computer model sees the target as a single, homogeneous slab of material, but in reality, it will be composed of a fabric over some type of substrate. This will be the subject of Section 4.2. First, we will characterize the ignition sources which the fabric will see.

4.1 IGNITION SOURCE CHARACTERIZATION

The characterization of the ignition source in our scenarios involves defining the size and radiant output of the radiating surface of the heating appliance. Reference 8 identifies four types of alternative heating devices which cause either many fires or a high probability of death per fire. These four heaters are wood stoves, portable kerosene heaters, gas-fueled, fixed area heaters, and portable electric heaters. These will be the ignition sources which we will consider.

4.1.1 *Rectangular Ignition Sources*

Two different types of rectangular heaters we need to consider are electric heaters (portable) and gas-fueled, fixed area heaters. There are a large variety

of sizes and powers of these types of heaters, and different usage patterns as well.

Stand-alone portable electric heaters, while designed to be used as supplementary heating of individual rooms, may also be used as a primary heat source in some instances. This type of heater is likely to be used for long durations and left unattended. The use of gas-fueled, fixed area heaters also lends itself to unattended operation, and in many instances is thermostatically controlled and runs automatically.

Since the dimensions and fuel types for these two types of devices are very different (it is hard to envision an electric heater as big as a gas wall heater), we will consider them separately.

4.1.1.1 Electric Heaters

A heater which produces heat by the use of electricity will generally produce that heat by means of resistive heating elements, and the heat produced will be radiated directly from those elements as well as being reflected from a built-in reflector. Some types of electric heaters also incorporate fans and a substantial portion of their thermal output becomes convective. Depending upon the temperature of the heating elements and the reflector material, the thermal radiation spectrum of the emitted heat flux will vary. Experimental results have shown that there can be ignition effects (changes in the ignition time) due to variations in the incident radiation heat flux spectrum [19,20], but since our model is not equipped to handle the spectrum of the incident heat flux, we will ignore effects of this type. We are therefore left with only three variables to describe the heater: its front surface width and height, and its total thermal output, P .

The length of the heater will show substantially more variation than the height. Baseboard units may be as much as several feet long, but are normally not very tall. Other portable units are wider than they are tall, but much closer to square. The height of these heaters can range from 3 or 4 inches for the baseboard units to 1 foot or so for the more square units. The width can range from approximately three feet down to less than foot.

The thermal output of the heater is more difficult to assess. A "1500 watt heater" does not necessarily output 1.5 kW of thermal energy due to losses from the heater as well as power consumption by such things as fans. A short discussion in [21] cites a value of 20 kW/m² heat flux measured at the guard of a 3 kW electric heater. Unfortunately, the dimensions of the heater are not given, so we cannot calculate the actual heater thermal output.

A survey of portable electric heaters for sale in southern California stores shows a general trend for available heaters to be in the 0.5 to 1.5 kW electric range (based on a small sample of less than 40 models). Table 6 gives the dimensions of the radiating areas, the heater power outputs, and the type of heater for those surveyed. It should be noted that all of the data we have obtained and especially that collected from area stores is pertinent to electric heaters which are on the market and being purchased today. It does not cover the electric heaters which are in use today but were manufactured 10 years ago under possibly very different regulatory conditions (the maximum allowed power from a portable electric space heater is 1500 W; at least in California in 1988.) We will, however, consider the number of these old heaters which are still in existence in Section 4.4 and in Appendix C.4.

4.1.1.2 Fixed Area, Gas Heaters

Fixed-area, gas fueled heaters come in many sizes and shapes, ranging from short, thick box-like units to tall, thin wall mounted ones. Reference 22 states

TABLE 6

Characteristics of portable electric space heaters surveyed.

Manufacturer	Model number	Type*	Power (W)	width (cm)	height (cm)
Patton	HF20G	c	500 1000 1500	13	13
Holmes Air	HFH-102	c	1000 1500	13	13
Holmes Air	HFH-503	c	500 1000 1500	13	13
Holmes Air	HFH-301	c	500 1000 500	13	13
Holmes Air	HFH-870	c	1000 1500	18	18
Rival	T760B1	c	1300 1500	13	13
Rival	T910	c	1300 1500	13	13
Titan	RT70	b	1300 1500	15	30
Robeson	1500	d	400 900 600 1050 1500	25 13 28	10 5 15
Arvin	30H21	b	1250 1500	25	18
Presto	O7876	a	1500	10	46
Arvin	30H25-01	b	1320	25	15
Lakewood	O792	c	1300 1500	15	15
Patton	HF 8	c	1500	13	13
Arvin	29H40	b	800 1500	15	10
Sears	36000	a	850	25	15
Sears	36011	b	1320	25	15
Sears	36012	b	1250 500	25	18
Sears	36101	a	1500	13	61
Sears	36410	b	1250 1500	76	13

a = radiative, b=mostly convective + radiative, c= mostly radiative + convective, d= either

that gas-fired heaters manufactured in the U.S. range from approximately 10000 to 85000 Btu/hr in fuel consumption and average approximately 50 to 60 percent efficiency in delivering useful heat to the room. Several gas-fueled wall units which are available in southern California were also included in the

survey of electric heaters and their dimensions and thermal output values are given in Table 7

TABLE 7
Characteristics of fixed, gas-fueled heaters surveyed.

Manufacturer	Model #	Gas input (W)	Thermal output (W)	Height (cm)	Width (cm)
Williams	14DV-3	4102	2871	71	46
Williams	22DV	6446	4512	78	91
Williams	30DV	8790	6153	78	91
Monterey	25GV-3	7325	-----	137	36
Sears	various	7179-16115	5742-12892	184-221	36

These numbers give us a general idea of the dimensions of the heaters we are analyzing and the thermal energy which they are capable of generating into a room, but we have no data on how much of this energy is in the form of radiation. We cannot even utilize the physics of a burning gas flame to estimate the radiant percentage since in most gas heaters, the flame is not visible and any radiant heat is from hot surfaces of the heater. Unfortunately, we also do not have data on the surface operating temperatures of these heaters. To estimate the radiant heat flux from these heaters, we will have to utilize a distribution of the fraction of the thermal heat generated by the heater which is generated as radiation and assess this distribution through some physical arguments and general knowledge.

The fraction of the heat from a burning object which is radiated away from the flame varies greatly, but is in the range of 20 to 60 percent for many materials. Reference 23 presents a table of values of the "radiative fraction" (percent of heat of combustion which is radiated from the combustion zone) for a variety of hydrocarbon pool fires of various sizes. Many of the pools are quite large (See Table 8) and do not apply to our situation (we do not have a pool fire either, but we will use the most appropriate data). This radiation

from the flame is intercepted by the structure of the heater and then these surfaces re-radiate it. We will assume here that the heater reaches a steady-state condition and all its heating surfaces will reach a steady state temperature in a short period of time. We then will assume that the heater will radiate outward as much heat from these surfaces as it is receiving from the gas flames in the form of radiation. Actually, there are inevitably some losses and we will take the radiative fraction of the gas flames to range from 20 to 50 percent of the total heat output of the heater.

TABLE 8

Radiative fraction of combustion for several hydrocarbon fuels.

Hydrocarbon	Pool size (m)	$\bar{x}$ Radiative output/ Combustion output
Methanol	1.22	17.0
LNG on land	18.0	16.4
"	0.4-3.05	15.0-34.0
"	1.8-6.1	20.0-25.0
"	20.0	36.0
LNG on water	8.5-15.0	12.0-31.0*
LPG on land	20.0	7.0
Butane	0.3-0.76	19.9-26.9
Gasoline	1.22-3.05	40.0-13.0*
Gasoline	1.0-10.0	60.1-10.0*
Benzene	1.22	36.0-38.0
Hexane	--	40
Ethylene	--	38

*In these cases, the smaller diameter fires were associated with higher radiative outputs.

4.1.2 Cylindrical Ignition Sources

We will consider two types of cylindrical ignition sources: kerosene heaters and wood-burning stoves. Neither of these types of heaters are always

cylindrical, and in fact, many are not, but we will approximate a heater such as a cubical wood stove as a cylinder. Our rectangular radiator model cannot model geometries such as a scenario having the target off one corner of a cubical radiator, and a cylindrical geometry will more closely approximate the radiator.

4.1.2.1 Kerosene Heaters.

Kerosene heaters are basically designed in two types: convective and radiative. We are interested in the radiative types, but have no data on the relative percentages manufactured between the two types. Two sources of information which give the thermal output of several radiant kerosene heaters are References 24 and 25. The object of the studies was to test the emissions of the heaters, but they attempted to use "typical" heaters in their work and thus we may assume that the values they give for the fuel input heating value are useful in describing these types of heaters. Reference 24 cites a fuel input rate of 7000 ± 100 kJ/hr (1944 ± 28 W) for 5 different heaters and [25] cites values of 8650, 8650, and 8230 kJ/hr (2403, 2403, and 2286 W) for three heaters in their tests. A third set of tests from [26] gives a heat release rate for a radiant heater of 8250 ± 260 kJ/hr (2292 ± 72 W). Another type of kerosene heater in this set of tests, a "multistage" heater has heat output rates of between 12900 ± 1170 to 15600 ± 600 kJ/hr (3583 ± 325 to 4333 ± 167 W) depending on its high/low setting. This type of heater is something of a crossbreed between the radiant and convective types. A few heaters for sale in a catalog (three convective and one radiative) had heat output ratings of from 2754 to 5860 W.

The heat output rates suggested above include both the convective and radiative portions of combustion. We must therefore correct these values to reflect only the radiative portion of the heat output. The table of radiative fractions of combustion (Table 8) can be of some use here also. Some of the

heavier hydrocarbons would be more applicable to the kerosene case, and as can be seen from the table, we have radiative fractions ranging from about 20 percent to almost 60 percent with several values around 40 percent.

Physical dimensions of the radiating portions of the heaters are a little harder to assess (unvented kerosene heaters have been banned from sale for residential heating in California). From pictures of kerosene heaters and a catalog selling them (Sears), we find that the radiating portion of these cylindrical heaters is not more than approximately 15 inches in height and not less than approximately 6 inches (38 cm and 15 cm). The diameter of these radiating portions ranges from around 6 inches to 10 inches (15 cm and 25 cm).

4.1.2.2 Wood burning Stoves.

Reference 27 is a description of an experiment designed to measure typical temperatures of the exterior surfaces and flues of several wood stoves as well as the temperatures of adjacent floors and walls. Five different stoves were tested whose physical characteristics are given in Table 9. Eighteen tests were made using these five stoves and the maximum surface temperatures recorded are presented in Table 10. The overload temperatures were recorded with the stoves intentionally overfueled.

As an estimate of the total heat flux from a stove of this type, we will use the maximum recorded temperature to describe the entire stove surface and from the dimensions given and using the black-body radiator approximation (Equation 16, where P_{stove} is the total heat radiated by the stove, A_{stove} is the surface area of the stove and the other terms are the same as in Equation 13) we arrive at the total radiant heat from each stove given as the last two columns of Table 10. The dimensions of the cylinders used to model these stoves will be derived by keeping the height of the stove equal to the height of

TABLE 9

Dimensions of the 5 stoves tested in [27].

NUMBER	STOVE TYPE	LENGTH(CM)	WIDTH(CM)	HEIGHT(CM)	ABOVE FLOOR (CM)
1	RADIANT	46	37	65	14
2	RADIANT	62	42	65	11
3	RADIANT	83	47	77	13
4	FRANKLIN	39	85	79	7
5	CIRCULATOR	53	89	54	11

TABLE 10

Stove surface temperatures (C)[27]. and estimates of radiative thermal output

APPL.#	SS TEMP(C)	MAX TEMP(C)	SS Q (est) (kW)	MAX Q (est) (kW)
1	332	393	9.2	13.5
1	344	460	9.9	19.8
1	312	378	8.0	12.3
2	377	401	16.1	18.6
2	346	378	13.3	16.2
3	434	386	33.5	25.3
3	409	415	29.0	30.1
4	322	733	15.8	129.4
4	297	630	13.3	84.0
4	278	-----	11.7	-----
4	319	694	15.5	110.5
5	433	525	29.7	48.4
5	436	497	30.2	42.0
2	425	488	21.4	30.3
2	386	395	17.0	18.0
2	386	408	17.0	19.4
2	407	452	19.3	24.9
2	337	377	12.5	16.1

SS=steady state, max=maximum, Q=Heat output, appl=appliance

the cylinder and equating the base area of the stove to the base area of the approximating cylinder.

$$P_{stove} = A_{stove} \epsilon \sigma T_{stove}^4 \quad (16)$$

4.2 TARGET OBJECT CHARACTERIZATION

The fabric material class we are analyzing may be found in various forms within a residence. It's normal use will be as a covering on some type of furniture, but the size of the piece of furniture as well as its construction may vary considerably, i.e., it may cover the back, sides or cushions of a couch, loveseat, chair, or even a separate pillow. The type of material under the fabric (the "substrate") will also vary considerably since it may be various types of padding, an interliner, or possibly a wood, plastic or metal portion of the frame of the piece of furniture.

From the viewpoint of the computer code, there are several thermophysical values needed to describe the target. These are:

- the target thermal conductivity
- the target density
- the target specific heat
- the target surface emissivity
- the target material ignition temperature.

As these properties can only be specified to apply to the entire volume of the target, it is necessary to choose them carefully so as to describe the composite material as accurately as possible.

For any scenario which we may envision our fabric to be involved in, it will be arranged as a thin covering over some other, thicker substrate. In most

cases, such as a furniture cushion, the substrate (a padding such as polyurethane foam) will be much thicker than the fabric. As this is the case, we may make some assumptions about the thermal properties which describe the target:

1. The fabric will be thermally thin compared to the substrate.
 - The thermal conductivity, density and specific heat of the substrate will control the internal heat transfer.
2. Radiation absorption in-depth in the target is ignored.
 - the emissivity of the fabric will control the radiation processes on the surface of the target.
3. Since it is the fabric which we are analyzing, and we are not modeling phenomena such as the melting away of thermoplastic fabrics (which might expose the substrate material to ignition before the fabric), the spontaneous ignition temperature of the fabric will be our ignition criteria.

4.2.1 *Fabric*

As discussed before, the values which we need to describe the fabric are the surface emissivity and the ignition temperature. In fabric ignition experiments in [28], 11 out of 20 tested fabrics meet our classification. Various thermophysical properties were measured for these fabrics, including the reflectance, transmittance and absorptance of the fabrics as well as piloted and spontaneous ignition temperatures. These properties were measured with two different heat sources: an unfiltered 3160 K tungsten lamp and the same lamp with a red filter ($0.6 \leq \lambda \leq 2.5 \mu\text{m}$). The measurements were made with new samples of the fabrics and then with samples that had been artificially charred to simulate their conditions at the time of ignition. The data is given in Table 11. Note that the emissivities given are equal to $(1 - \text{reflectivity})$ since we do not model in-depth radiation absorption.

TABLE 11

Fabric Emissivity and Ignition Temperature Data [28]

Fabric GIRCFF no.	Fabric Composition	unfiltered heat source	red filter over heat source	charred fabric (unfiltered source)	Ignition Temp. (°C)	
					Spont.	Pilot.
1	65/35% PE./C.	0.395	0.478	0.634	416-409	337-331
4	100% Cotton	0.550	0.509	0.599	297-280	290-280
5	100% Cotton	0.467	0.479	0.509	327-301	311-301
6	65/35% PE./C.	0.419	0.419	0.661	416-409	345-347
8	65/35% PE./C.	0.438	0.540	0.654	450-416	316-304
9	100% Cotton	0.319	0.377	0.373	308-297	297-290
10	100% Cotton	0.582	0.594	0.781	443-429	351-339
16	50/50% PE./C.	0.387	0.501	0.678	473-466	360-353
17	65/35% PE./C.	0.515	0.536	0.745	480-463	384-368
18	100% Cotton	0.401	0.427	0.473	311-301	294-278
19	100% Cotton	0.410	0.398	0.752	497-480	329-316

C. = cotton, PE = Polyester

4.2.2 Substrate

There are various types of materials which may lie under our cloth which we need to consider. Possible substrates are: wood, polyurethane foam, plastic, metal, cotton batting, an interliner (some other type of less or non-combustible fabric), or even air. The dominant type of substrate, however, will be one of the padding types. In Reference 29, four classes of substrate were identified as used in upholstered furniture: cotton, polyester, and mixed fiber battings and polyurethane foam. Values of the thermal conductivity, specific heat, and density are thus needed for these classes of substrate materials.

For polyurethane foam, [30] gives values for the thermal conductivity of flexible polyurethane foam to range from 0.033 W/mK at zero degrees C to

0.040 W/mK at 70 degrees C for foam densities ranging from 20 to 70 kg/m³. Typical foam densities are also cited to be between 20 and 45 kg/m³. The specific heat of polyurethane foam was not available and will be taken as 1100 J/kgK, a value just slightly higher than that of air, since a foam is mostly air in the first place.

For cotton, [31] gives values of 80 kg/m³ for the density, 0.06 W/mK for the thermal conductivity and 1300 J/kgK for the specific heat. The form of the material is not given.

Values for polyester and mixed fiber battings are not available as such. References 32-34 provide data for many different types of solid plastics including polyester. A value for the thermal conductivity of solid polyester is 0.29 W/mK [34]. Also from [34] are 1173 J/kgK for the specific heat of solid polyester and 1378 kg/m³ for the density. Reference 32 gives thermal conductivities, densities and specific heat values for a variety of solid plastics. The thermal conductivities range from 0.126 to 0.24 W/mK, the specific heat values range from 1131 to 2221 J/kgK, and the densities range from 850 to 1335 kg/m³.

Now, we know that batting is not the same as solid polyester or cotton. It is a "tuft" of fibers which includes a lot of air space. At room temperature, the thermal properties of air are: density, 1.16 kg/m³, specific heat, 1007 J/mK, and thermal conductivity 0.026 W/mK [31]. We have no data on the void space in a batting material, and in fact, the amount of space will probably decrease with use as the batting becomes compressed. We do not expect to have the very high void space as in foams (note that the polyurethane foam thermal conductivity is very close to that of air) and we will assume that the void space in a batting material will be between 20 and 50 percent.

Using this assumption on the batting void space, we have the following ranges:

For cotton batting:

- The thermal conductivity can range from about 0.043 to 0.053 W/mK
- The specific heat can range from about 1154 to 1240 J/kgK
- The density can range from about 40 to 64 kg/m³

For polyester batting:

A preliminary calculation with the above void space values and the thermal parameters for solid plastics showed a very high value range for the density of the polyester batting. We must thus assume that in the transition from solid plastic to fiber, additional space is added in the fiber itself. We will take this additional space to be 0.5 of the fiber volume.

- The thermal conductivity can range from about 0.09 to 0.13 W/mK from the one polyester data point or from 0.02 to 0.13 W/mK including the data from other plastics.
- The specific heat can range from 1049 to 1073 J/kgK from the one polyester data point, or from 1038 to 1493 J/kgK including the data from other plastics.
- The density can range from 345 to 551 kg/m³ from the one polyester data point, or from 212 to 534 kg/m³ including the data from other plastics.

This data is summarized in Table 12.

4.3 SCENARIO DESCRIPTION

We have now provided the physical values and data to describe our heaters and target materials, but we have not yet discussed how these heaters and targets actually get together in a scenario. In Section II, a distribution for

TABLE 12

Thermophysical data for substrate material classes.

Material	k (W/mK)	c_p (J/kg K)	ρ (kg/m ³)
Polyurethane foam	0.04	1100	20. - 45.
cotton batting	0.043 - 0.053	1154 - 1240	40. - 64.
Polyester batting (PE data only)	0.09 - 0.13	1049 - 1073	345 - 551
with other plastics	0.02 - .013	1038 - 1493	212 - 534

k = thermal conductivity, c_p = specific heat, ρ =density

fr(exp) of the target to the heater was derived, but no physical limitations were placed on the geometries between the target and heater or even on the target and heater types (except that the target had to be a consumer product and the heater had to be an alternative heating appliance). Here we must consider the problem of how to probabilistically combine the heater types and the target types in a coherent framework so as to obtain the f(ign|exp).

4.3.1 *Definition of the Heater Critical Areas*

For each type of heater which we have defined, there exists a range of thermal output depending upon the size and power of the specific heater in question. The larger heaters, such as a gas wall heater or a wood stove, put out

substantially more heat than some of the smaller heaters, but put it out over a much larger heater surface area. If the smallest heater of each type were to output the highest heat output for that type of heater, it would put out the most intense heat flux field around itself of any heater of that type.

The target materials which we are modeling exhibit a minimum incident heat flux at which point their ignition time is effectively infinite. This can be seen in Figure 22, where each of the times to ignition tend to get very large as the incident heat flux drops below 10 kW/m^2 . The fabric/padding combinations in Figure 22 were intended to show the incident flux/ignition time relationship for the range of fabric/padding combinations whose ignition difficulty ranges from easy to difficult. The minimum incident flux for which ignition was observed was 5.6 kW/m^2 . Thus, we should be reasonably assured that, if the maximum heat flux which our target receives is below this value, ignition will not occur. Thus, we may define a "critical area" in front of or around each type of heater within which, for the heater power/heater size combination which yields the most intense heat flux field around itself, the heat flux will always be greater than some minimum value. We will take this minimum value to be 5.0 kW/m^2 . We may then say that any target item which is inside this critical area is being exposed to the heater, and the frequency with which it is exposed will be a combination of the frequency of exposure distribution calculated in Section II and the proportion of heaters of the type exposing the target in any specific scenario (See Section 4.4). Note that this definition of the critical area is dependent upon material dependent results. To analyze another type of material, (e.g., wood), a minimum heat flux for ignition would have to be defined for this material class and the critical area boundary calculations repeated. Not performed here, but easily accomplished, would be a minimum flux contour map in front of or around each heater so that the calculations would not have to be repeated for each different material with differing minimum heat fluxes for ignition.

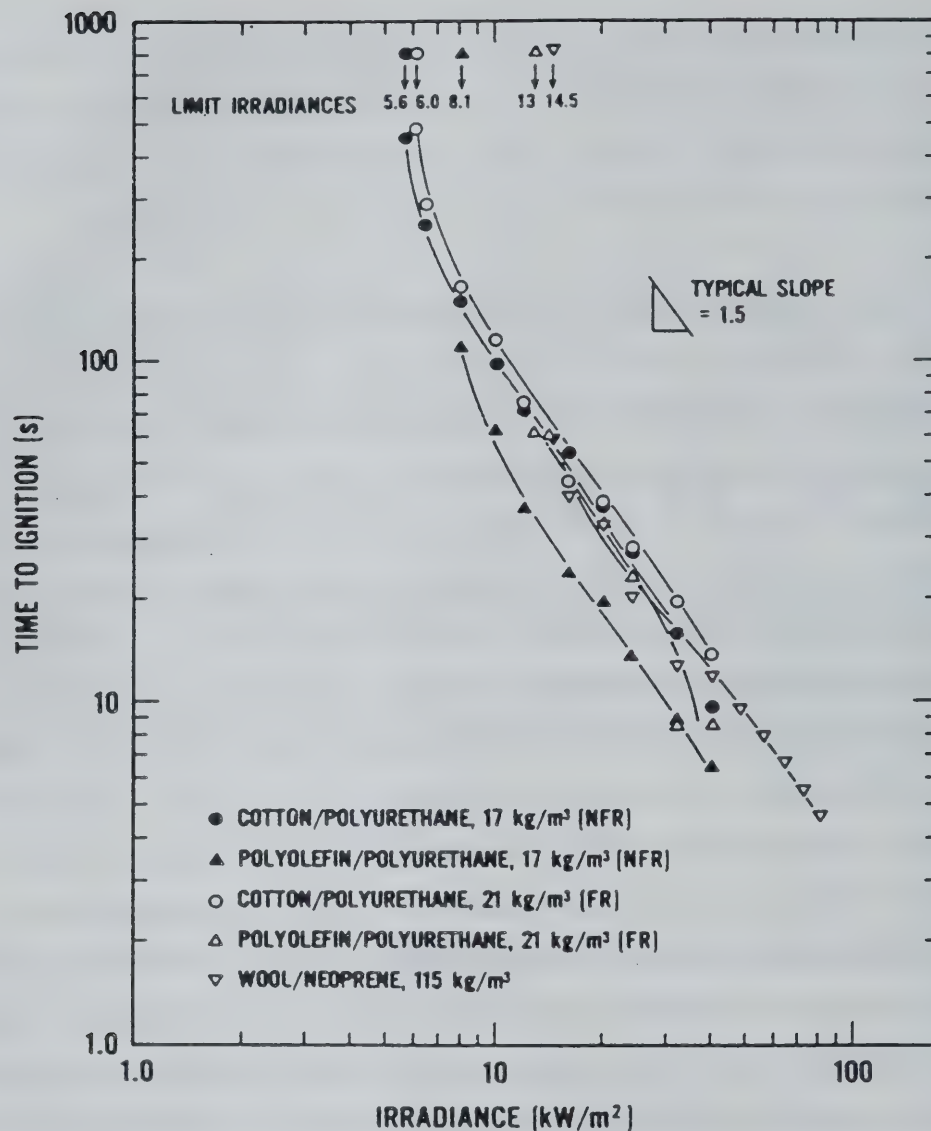


Figure 22: Typical ignition curves [9]

4.3.2 Calculation of the Heater Critical Areas

From the data given in Sections 4.1.1.1 - 4.1.2.2, we may calculate the critical areas described above. We must be careful when assessing the critical areas to only include the areas in which ignition is possible. This is because our choice of a critical area will have a substantial effect on the final outcome of the f(ign|exp) calculations. This effect can be seen from considering what

would happen if we took an arbitrarily large critical area. If we then did our physical calculations with the ignition code, many of our "trials" would end up with no ignition because they were too far from the ignition source. If the distribution of the target position within the critical area was taken to be uniform (which it will be assumed is one possible case in Section 4.4), and the critical area cut in half, but still large, there will be little change in the ratio of ignitions to non-ignitions, since all of the area which was removed, was area in which we know physically that the probability of ignition was zero. If the critical region is reduced further, more and more area in which no ignition is possible will be removed until we are left with a region in which the probability of ignition is not known to be zero from physical factors and thus whether a given target ignites will be governed by only the heat flux impinging upon the target and the thermal properties of the target. This is what we mean by a target being exposed to the heater and why we have chosen the 5 kW/m^2 boundary to be the edge of our critical area. Any larger area would include some scenarios in which we know the target is not really being "exposed" to the heater. The exact value of 5 kW/m^2 is not a precisely known value, and in fact could have been defined as 2 kW/m^2 , or 7 kW/m^2 , or some other such number. If desired, the critical area boundary could be considered to be another uncertain variable and a distribution for the boundary for each heater assessed. This, however, would add additional complexity to the calculations which is unnecessary since we have a fairly "accurate" boundary flux value from experimental evidence. The point is that the choice must be made on the basis of where we think the $f(\text{ign}|\text{exp})$ value reaches zero for any conceivable scenario. We have decided that a minimum heat flux at the target of 5 kW/m^2 defines this boundary.

For electric heaters, we can see from Table 6 that the maximum thermal output is 1500 W, the minimum height is 5 cm. and the minimum width is 10 cm. These height and width measurements are not for a heater which puts out 1500 W, however. The lowest combined height/width measurement which is

associated with a 1500 W output is 15 cm. wide by 10 cm. tall. This heater puts out the heat flux field indicated in Figure 23. Figure 24 shows the x, z contour for which the heat flux at a target is 5 kW/m^2 . The flux is less than 5 kW/m^2 outside of this contour and greater inside it.

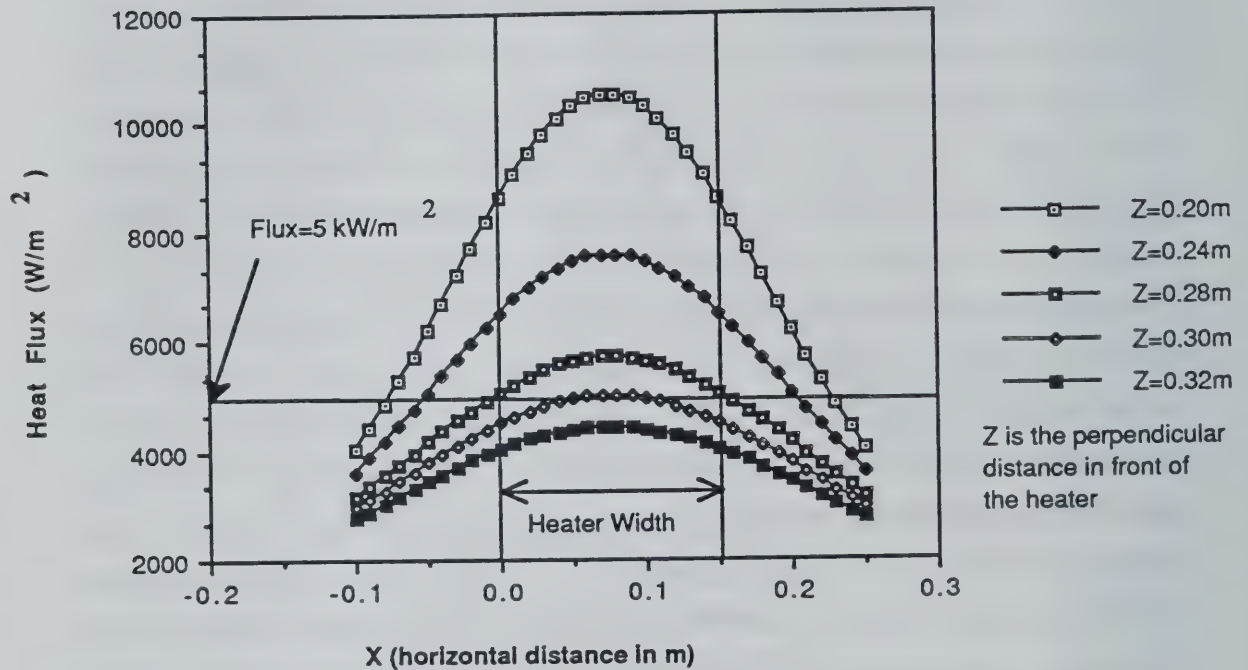


Figure 23: Heat flux field in front of a 10x15 cm electric heater radiating 1500 W

This boundary thus defines our critical area. A rectangular region which includes this critical area extends from approximately 10 cm on either side of the heater and 30 cm. in front of it. We will use this same definition of the critical area for electric heaters of other sizes; i.e., 10 cm to either side and 30 cm in front since any larger heater putting out the same 1500 W will actually have a smaller 5 kW/m^2 boundary and thus this definition of the critical area effectively extends to the point at which we consider the f(ign|exp) to be zero for any size/power of heater or type of upholstered furniture target. It should

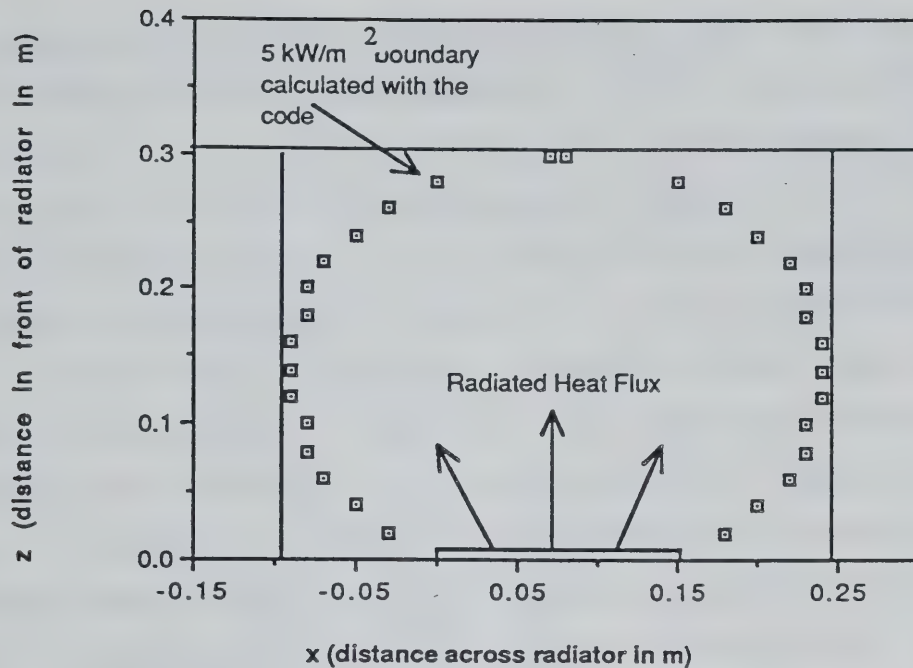


Figure 24: 5 kW/m^2 contour for a $10 \times 15 \text{ cm}$ electric heater radiating 1500 W

be noted that the heater thermal output bears very little correlation to the size of the heater radiating area. (See the electric heater data analysis in Appendix C.) This means that we may expect any of the possible heater sizes to output any of the possible thermal heat values.

The derivation of the critical area for a gas heater follows the electric heater case closely. Our data base is, however, very limited. The smallest gas wall heater in our small survey is approximately 0.46 m wide and 0.71 m tall. If we take the bottom 6 inches ($.15 \text{ m}$) (for the pilot and burner assemblies) and an inch around the other three sides to be non-radiating areas, then the minimum radiating area is approximately $0.41 \times 0.53 = 0.217 \text{ m}^2$. The maximum radiating area in our survey is approximately $0.31 \times 2.03 = 0.629 \text{ m}^2$ in area.

The thermal output of the small heater described above is given by the manufacturer to be 2871 W. The largest thermal output of a gas heater (from [22]) is approximately 15 kW. We must also factor in the radiative fraction, which we have discussed to range up to approximately 0.50. This gives the high and low fluxes to be 1435 W and 7.5 kW. If we couple the small heat output with the smallest heater and the largest heat output with the largest heater (which very roughly corresponds to the way the heater outputs are really correlated to the heater size), we get the 5 kW/m² contours shown in Figures 25 and 26. We can see from these two figures that the contour for the large heater with the highest output will encompass the contours for smaller heaters with lower outputs. Thus, we may take the critical area for a gas wall heater to be described by the contour for the large heater which is approximately 3 cm to either side of the heater and 32 cm in front of it.

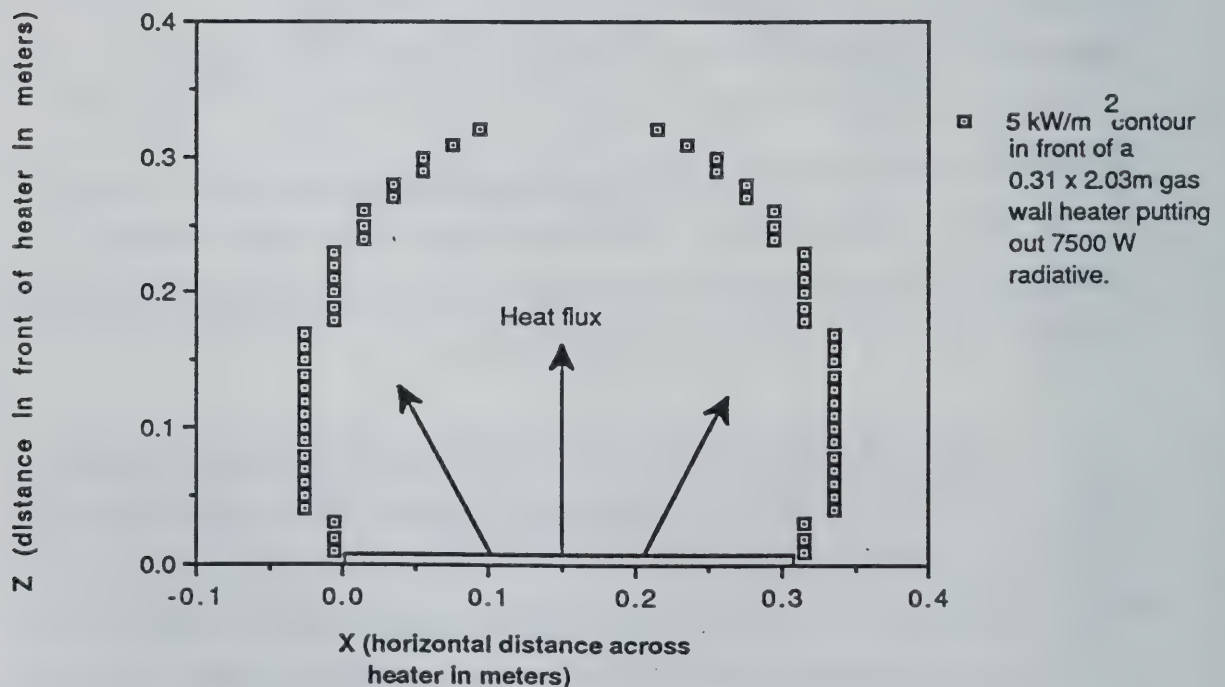


Figure 25: 5 kW/m² contour for large gas wall heater.

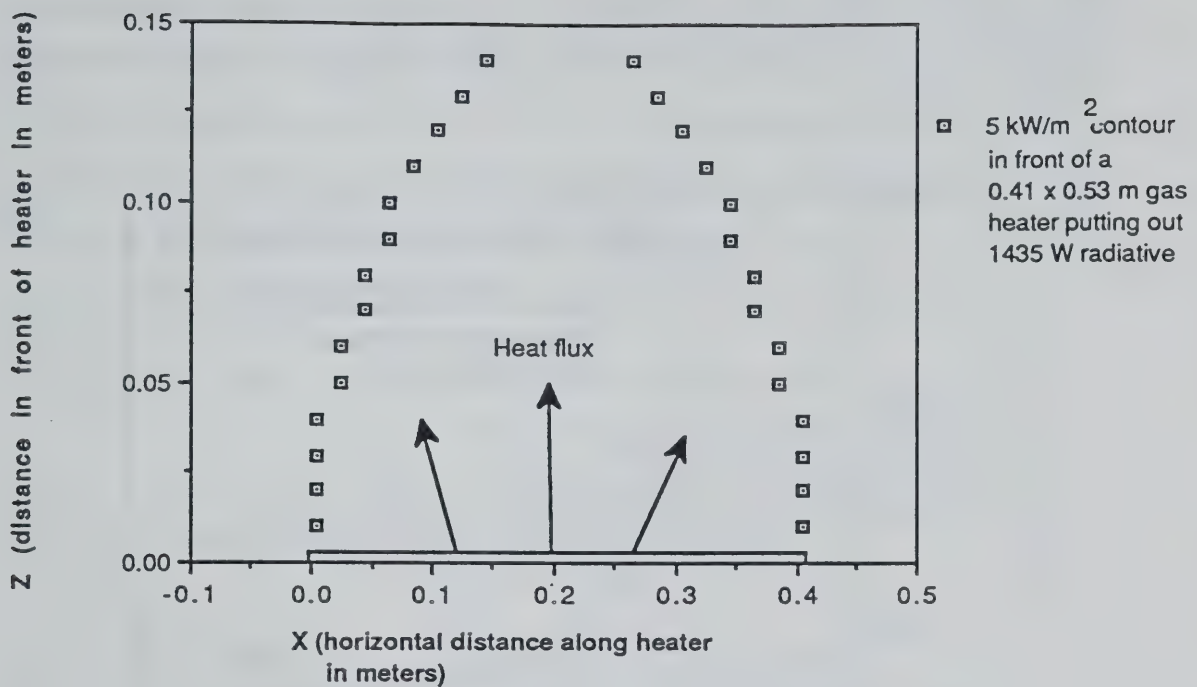


Figure 26: 5 kW/m^2 contour for small gas wall heater.

The critical area for a kerosene heater is defined by the maximum radius for which the maximum heat flux is 5 kW/m^2 . For this calculation we will use two geometries: the maximum height (15 in.; 38 cm) and radius (5 in.; 12.5 cm) cylinder with the maximum heat output (20000 Btu/hr; 5860 W), and the minimum height and radius ($R = 7.5 \text{ cm}$, $H = 7.5 \text{ cm}$) with the same 5860 W heat output to define the area. Since the value of 5860 W is the total convective and radiative heat flux, we will actually use the value $3516 \text{ W} = 5860 \times 0.6$, where 0.6 is the maximum radiative fraction from Table 8. As can be seen in Figure 27, the radial decrease of the heat flux level gives a maximum radius for the 5 kW/m^2 to be located at approximately 28.5 cm from the cylinder center for both heater sizes. Since there is only a 5 cm difference in the radii of the smallest and largest heaters, we will take 21 cm from the heater edge to be the critical area radial boundary. This value is 28.5

cm - 7.5 cm, which is the distance from the most intense kerosene heater postulated and will include the 5 kW/m^2 boundary from all other postulated kerosene heaters.

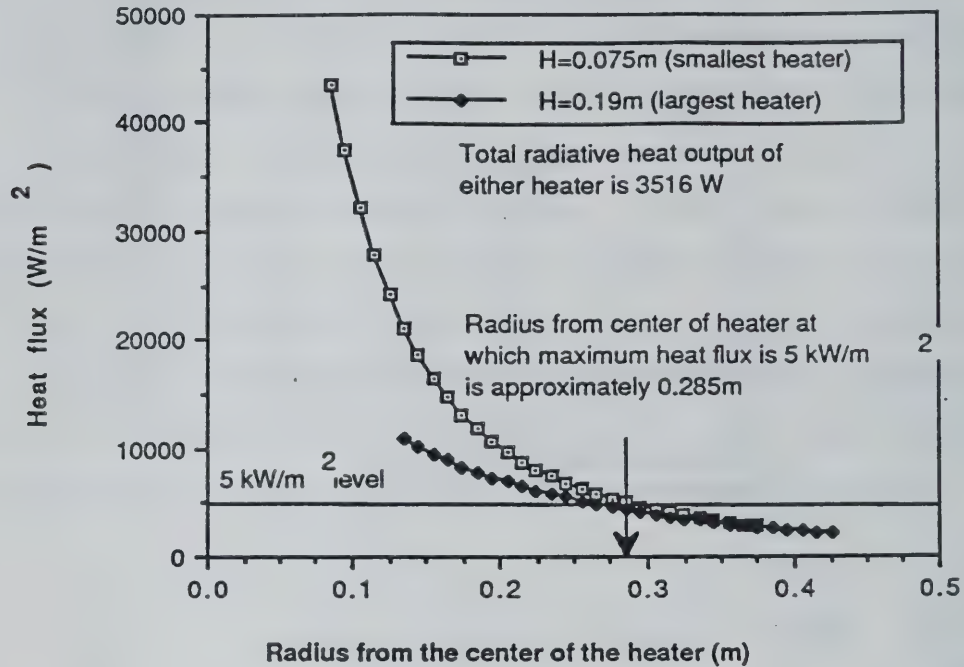


Figure 27: Radial flux distribution from a cylindrical kerosene heater

The critical area for a wood stove is defined exactly like that of a kerosene heater. From Tables 9 and 10, we can see that the stove with the largest approximating cylinder is stove number 3 at 83x47x77 cm (cylinder radius=0.35 m and height 0.77 m). The stove with the smallest cylinder area is cylinder 1 at 46x37x65 cm (cylinder radius=0.23 m and height 0.65 m). Since we are assuming the stove temperature is uncorrelated to the stove size (see Appendix C for the basis for this assumption), either the smallest or largest cylinder may assume any of the possible heat output values. If we take the maximum estimated heat output of 129400 W and calculate the radial heat flux distribution for each of the two cylinders, we get the radial flux

distributions shown in Figure 28. The results show that the radial distance from the center of either stove at which the heat flux level drops to below 5 kW/m^2 is approximately 1.75 m. Thus, as in the kerosene heater case, we will calculate the critical area from the most intense wood stove as being $1.75 \text{ m} - 0.23 \text{ m} \approx 1.5 \text{ m}$ from the stove edge, which we will use as the value of the critical radius for a wood stove.

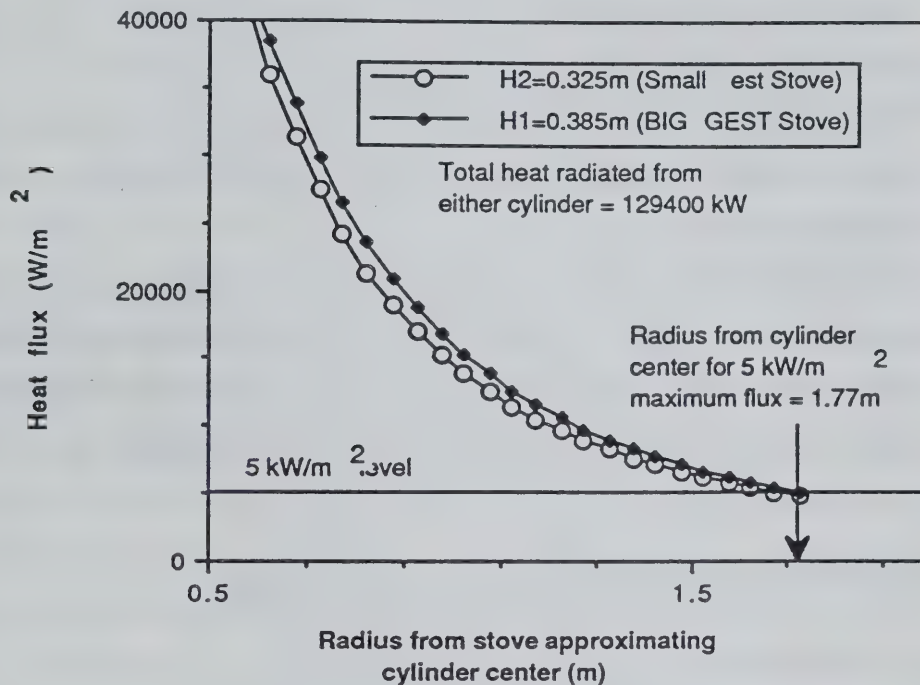


Figure 28: Radial flux distribution from a wood stove.

4.3.2.1 Critical Area Summary

The critical areas which we have now described for each of the four heater types in our study (portable electric, fixed gas- fueled, portable kerosene, and wood stoves) are summarized below, the dimensions indicated being the

distances at which the heat flux from any heater of the type will not be more than 5 kW/m^2 .

- For a rectangular portable electric heater, the critical area is defined as a rectangular area in front of the heater which extends 10 cm to either side of the heater and 30 cm perpendicular in front of it.
- For a rectangular fixed, gas-fueled heater, the critical area is defined as a rectangular area in front of the heater which extends 3 cm to either side of the heater and for 32 cm perpendicular in front of it.
- For a portable kerosene fueled heater, the critical area is defined as a circular region extending from the surface of the cylindrical heater radially for 0.21 m.
- For a fixed wood stove, the critical area is defined as a circular region extending from the surface of a cylinder which is used to model the stove (area of the base of the cylinder equal to the area of the base of the stove and having the same height as the stove) radially for 1.5 m.

4.4 CALCULATION OF F(IGNITION | EXPOSURE)

The last quantity which we need to calculate is the fraction of times that a certain target object being modeled will ignite when it is exposed to the ignition source. We have previously defined the exposure of the product to be modeled by a frequency ($fr(exp)$, Section II) with which a product is inside a specified critical area around an ignition source (a heater, Section 4.3.1). We must now model:

1. The placement of the target object within the critical areas.
2. The heat transfer to the target object and subsequent ignition of that object (if any). The computer model of Section III will be used to do this.

3. Treatment of the uncertainties in the target thermophysical parameters and the heater dimensions/thermal outputs.

We will treat the placement of the target within the critical area with two different assumptions: that the target's closest point is distributed uniformly within the critical areas and then that the target's closest point is distributed with a triangular distribution as shown in Figure 5. This means that for the cylindrical cases, the side of the target closest to the cylinder will have a radius which is distributed either uniformly or according to the triangular distribution in Figure 5 between almost touching the cylinder and the critical radius for the heater type. The second assumption is probably more realistic since people do tend to try to be careful and they are more likely to place the target farther from the heater than closer. For the rectangular radiator, the distribution in perpendicular distance in front of the heater will be either uniform or triangular as discussed for the cylindrical case, the distribution across the width of the heater will always be uniform and the angle of orientation Φ of the target with respect to the heater will be uniformly distributed about zero degrees with ± 10 degrees as the boundaries of the distribution.

As discussed in Section I, there exists in the U.S. both a set of existing upholstered furniture and a set of existing heaters of the four types we are considering. We are assuming that the distribution of upholstered furniture will have certain characteristics of its padding materials (See Appendix C.4) and that we may recover all of the pieces with the fabric we are analyzing. We are also assuming that the distributions describing the physical size and the power outputs of the heaters can be described by data collected on heaters which are being sold now. Since many of these heaters were built and sold some years ago, this may or may not be the case, but the assumption is adequate for our purpose.

The distributions for the various thermophysical properties, geometrical descriptions, power outputs, etc. of the upholstered cushion and the heaters are assessed in Appendix C. These distributions are summarized in Table 13 and 14.

To calculate the distribution of $f(\text{ign}|\text{exp})$, we will do the following:

1. Select a piece of furniture from the set of furniture by sampling from the distributions describing the thermophysical properties of the furniture covering and padding. The variables sampled are the cover fabric emissivity and ignition temperature and the substrate thermal conductivity, density and specific heat
2. Select a heater type and the physical characteristics of that heater from the relevant distributions for the different types of heaters. The variables sampled are the heater length and width, or radius and height, and the heater total power output. The heater type will be assumed to be in proportion to the existing proportion of different heater types, i.e., the heater population is approximately 50 percent portable electric heaters, 20 percent kerosene heaters, 20 percent wood stoves and 10 percent fixed, gas fueled heaters [8]. Thus, if we do 10 trials, there will be 5 electric heater scenarios, 2 wood stoves, 2 kerosene heaters, and 1 gas heater.
3. Select the physical placement of the piece of furniture with respect to the heater within the critical area using the uniform or triangular distribution assumption discussed above. Depending upon the type of heater chosen, this will mean choosing either a target radius in front of a cylindrical heater or a (X, Y) value and angle for a target in front of a rectangular heater (where X is the distance in front of the heater and Y is the position across the heater).
4. Using the computer code, calculate the thermal response of the furniture cushion and see if and when the ignition temperature is exceeded. If it

TABLE 13

Summary of target scenario distributions

Furniture Cover Fabric			
Emissivity <u>Histogram</u> Pr(0.65-0.75) = 0.10 Pr(0.75-0.85) = 0.20 Pr(0.85-0.95) = 0.70		Ignition Temperature (C°) <u>Histogram</u> Pr(250-300) = 0.09 Pr(300-330) = 0.27 Pr(400-450) = 0.36 Pr(450-500) = 0.27	
Furniture Substrate			
PU Foam	Cotton Batting	PE Batting	Mixed Batting
k (W/mK) <u>Point Value</u> = 0.04	k (W/mK) <u>Uniform</u> a = 0.043 b = 0.053	k (W/mK) <u>Uniform</u> a = 0.09 b = 0.13	k (W/mK) <u>Uniform</u> a = 0.06 b = 0.10
c _p (J/kgK) <u>Point Value</u> = 1100	c _p (J/kgK) <u>Uniform</u> a = 1154 b = 1240	c _p (J/kgK) <u>Uniform</u> a = 1050 b = 1075	c _p (J/kgK) <u>Uniform</u> a = 1086 b = 1182
ρ (kg/m ³) <u>Uniform</u> a = 20 b = 45	ρ (kg/m ³) <u>Uniform</u> a = 40 b = 64	ρ (kg/m ³) <u>Uniform</u> a = 212 b = 534	ρ (kg/m ³) <u>Uniform</u> a = 100 b = 370
Proportion= 0.4	Proportion= 0.4	Proportion= 0.1	Proportion= 0.1

TABLE 14

Summary of heater scenario distributions

Heater Types			
Portable Electric	Fixed, gas fuel	Port. Kerosene	Wood Stove
Width (m) <u>Lognormal</u> Mean = 18.6 SD = 11	Width (m) <u>Uniform</u> a = 0.31 b = 0.86	Radius (m) <u>Uniform</u> a = 0.075 b = 0.125	Radius (m) <u>Uniform</u> a = 0.23 b = 0.39
Height (m) <u>Lognormal</u> Mean = 17 SD = 10	Height (m) Inverse Linearly Correlated to the width	Height (m) <u>Uniform</u> a = 0.15 b = 0.38	Height (m) <u>Uniform</u> a = 0.54 b = 0.79
Power (W) <u>Discrete</u> Pr(500) = 0.18 Pr(1000)=0.23 Pr(1300)=0.23 Pr(1500)=0.36	Power (W) <u>Lognormal</u> Mean = 2773 SD = 1255	Power (W) <u>Lognormal</u> Mean = 1286 SD = 555	Power (kW) <u>Lognormal</u> Mean = 27 SD = 28
Proportion= 0.5	Proportion= 0.1	Proportion= 0.2	Proportion= 0.2

is exceeded, then this scenario contributes an ignition to the $f(\text{ign}|\text{exp})$ calculation for this piece of furniture.

5. Using the same description of the piece of furniture, repeat steps two through four to generate another ignition/non-ignition trial.
6. We will use 500 trials per piece of furniture, which will give a resolution of $f(\text{ign}|\text{exp})$ of $1/500 = 0.002$, where $f(\text{ign}|\text{exp})$ is calculated as the number of ignitions observed divided by the number of trials for this piece of furniture.
7. Now repeat steps one through six to generate another estimate of $f(\text{ign}|\text{exp})$ for another piece of furniture from the set of furniture. We utilize a set of 10 different furniture samples to generate a set of estimates for $f(\text{ign}|\text{exp})$ for the set of furniture throughout the U.S. with the cover fabric we are analyzing. This requires 5000 code runs (10 pieces of furniture x 500 scenarios per piece). The resulting set of values for $f(\text{ign}|\text{exp})$ is a sample from the state-of-knowledge uncertainty distribution of $f(\text{ign}|\text{exp})$ for the set of furniture. Thus, from this sample, we form the distribution of $f(\text{ign}|\text{exp})$.

To do the selection of parameters values from the parameter distributions, we use two techniques; Latin Hypercube sampling [35] and Monte Carlo sampling. Latin hypercube sampling is simply a restricted form of Monte Carlo sampling in which the parameter distributions are divided into some number of equally probable intervals, a value is picked randomly in each interval (on the basis of the probability distribution within that interval) for each parameter, and the resulting sets of parameter values combined randomly. This method of sampling has the advantage of guaranteeing that all portions of a given distribution will be sampled, thus it is very useful for small samples such as the ten chairs in our calculations. We therefore use Latin Hypercube sampling to choose the parameter samples for the ten chairs in our calculations.

The heater parameters and the critical area target placement distributions, however, have no such small sample problem and plain Monte Carlo sampling is used to choose parameter values from the distributions. In both types of sampling, a computer code [36] was used to do the sampling.

As expected, the fraction of ignition values are all low, ranging from three out of 500 to 36 out of 500 ($f(\text{ign}|\text{exp})$ from 0.006 to 0.072). A histogram of the ignition fraction results is given in Figure 29. This sample has a mean = 0.0288 and a standard deviation of 0.0186. Thus, this histogram is the distribution of the $f(\text{ign}|\text{exp})$ which we will use to assess the $\text{fr}(\text{ignition})$ of our cotton/polyester fabric. Combining this distribution with the distribution for the frequency of exposure from Section II, we get the final distribution of the $\text{fr}(\text{ignition})$ as shown in Figure 30, which has a mean of 9.7×10^{-5} and a standard deviation of 1.96×10^{-4} .

Another benefit of the calculations is a distribution of the time to ignition of a chair exposed to a heater. Each ignition which occurred on any chair had a specific time at which it occurred, but the distribution of the times of all the ignitions would be useful for doing an interruption/detection/suppression analysis. The processes of ignition and fire growth, and detection and suppression are competing in time during a scenario. Many different things could interrupt the ignition process, some of them mechanical and some of them human. A short discussion of the interactions of the building occupants in the fire scenario is given in Section 4.5. The distribution of the ignition time for the uniform distance assumption scenarios is shown in Figure 31. Note that our model shows that most ignitions will occur within 5 minutes or so, but Figure 31 shows ignition times up to fifteen minutes, and actually, there are four points left off of the plot for clarity which range up to 3660 seconds.

The above analysis utilizes a uniform distribution for the distance of the closest point on the surface of the target object to the heater surface. As

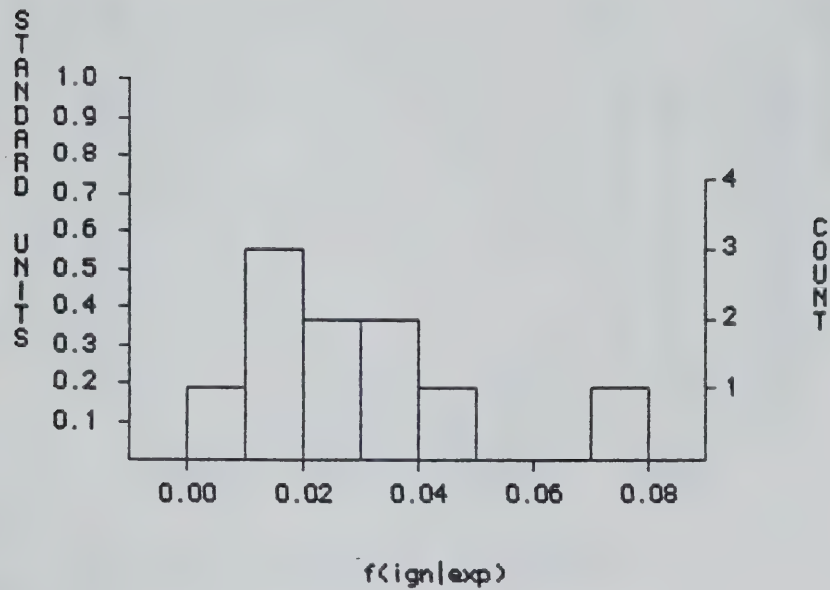


Figure 29: Distribution of $f(\text{ign}|\text{exp})$ with uniform distance distribution assumption

discussed in Section I, another possible choice for the distribution of the target distance, which may be more realistic, is a triangular distribution. Repeating the calculations from the uniform model scenarios by utilizing the same chair and heater parameter samples and changing the target distance distribution to triangular for all of the heater types, we get $f(\text{ign}|\text{exp})$ values which are somewhat lower than the uniform distribution results. The $f(\text{ign}|\text{exp})$ values here range from 0 to 10 ignitions in 500 scenarios. This calculation shows the sensitivity of the method to critical area assumptions and the importance of defining the critical area as precisely as possible.

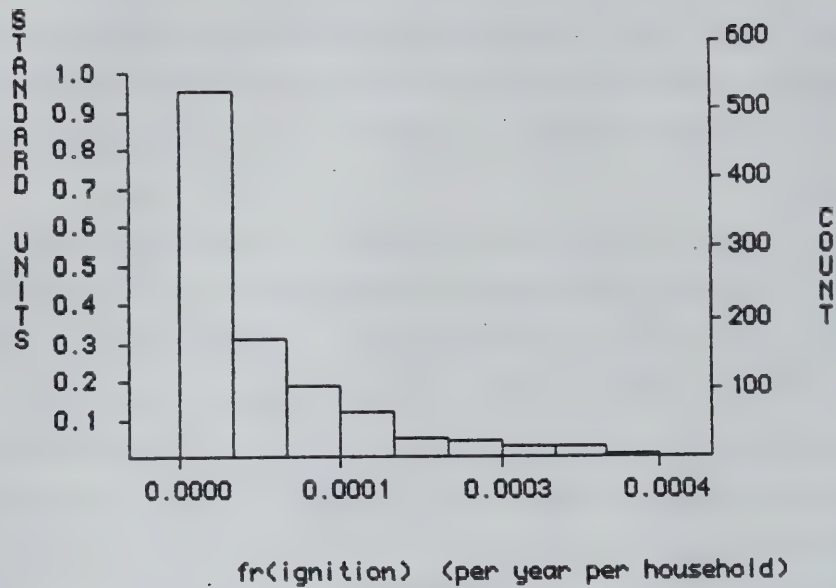


Figure 30: Distribution of $fr(ignition)$ with uniform distance distribution assumption

4.5 OCCUPANT EFFECTS NOT MODELED

The last term in Equation 5 requires the modeling of occupant actions on the progression of the ignition scenario. We are not modeling this term in this work, but a discussion of the possible effects may be useful to future research.

The effects which the occupants of a residence may have on the ignition scenario essentially involve the interruption of the heating of the target object before it reaches its ignition conditions. Since we have assumed that the scenario is caused by the target being too close to the ignitor (Section 1.1), the building occupants are also implicitly involved in placing the target too close to the heater or vice versa (such scenarios as a wood stove being installed too

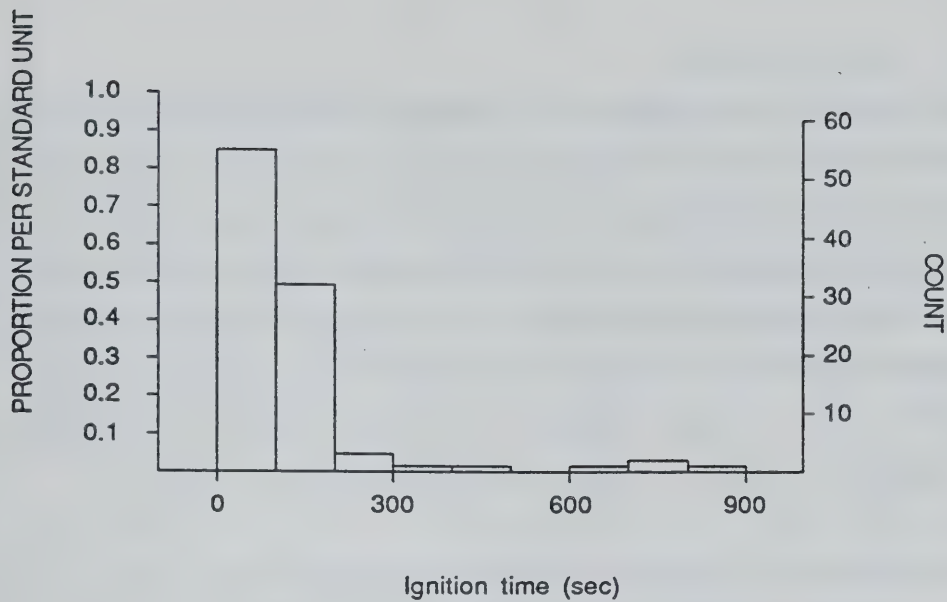


Figure 31: Histogram of the time to ignition

close to a wall are deemed not to involve the ignition of "consumer products" and are ignored).

In order to interrupt the heating process, the occupant must detect the problem and act on it. This would indicate that there will only be an occupant effect if:

1. There are occupants in the residence and
2. the occupants who are present are able to detect and respond to the problem.

Thus, the number and type of occupants which are in the residence at any specific time is important, and their states and subsequent actions will be affected by such things as the time of day at which the ignition scenario is happening.

4.6 CONCLUSIONS

The objective of this work is to develop a methodology for assessing the frequency of ignition of consumer products in buildings. We have approached the problem by analyzing the events which occur during an ignition scenario and using statistical data and physical modeling to describe these events. The frequency of exposure and fraction of ignitions given exposure are treated for a specific ignitor and product combination, but are general concepts which may be applied to any combination of ignitor and product by tailoring the probabilistic and physical analysis to that ignitor and product.

The consumer product frequency of exposure distribution can also be tailored more specifically to the realities of the market for a new product by assessing the product's potential market share and proportioning the $f(\text{exp})$ values appropriately.

The assumption in our calculation of $f(\text{ign}|\text{exp})$ that the substrate for the material is equivalent to the status quo distribution of padding types is also not fixed. To more accurately assess the performance of a new product in its "typical" environment, an analyst may want to utilize not only the new product's market share numbers, but also the padding distribution for chairs which are being built today instead of how they were built over the last 30 years.

Finally, note that the physical model presented in this work is not the only model which could have been used to assess the $f(\text{ign}|\text{exp})$ values. Other simple analytic or possibly one dimensional numerical calculations could have been postulated as our model for the physical processes which are going on in our scenarios. We decided, however, to attempt to put as much "realism" into the calculations as was deemed feasible. Even so, the uncertainty propagation work in Section 4.4 could not be done on a micro-computer due to the length of time involved. (The code runs fine on a micro, but at 10 to 30 minutes a

scenario, the 5000 uncertainty propagation scenarios made using the IBM mainframe at UCLA a necessity. On the mainframe it was even a matter of 90 CPU minutes or so.) Any other model which an analyst would wish to use to model the physics of the scenario would, however, be utilized in precisely the same manner as the code presented here. The model inputs might be different (e.g., if the model considered chemical kinetics or other such phenomena), but the parameter distribution assessment and uncertainty propagation would still be done. Approximation methods such as response surface modeling [37] might also be used to allow the two dimensionality of the model (which is the reason that the calculations took so long) while making the calculational effort feasible for a microcomputer or for a larger number of product types.

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Appendix A

RECTANGULAR RADIATOR VIEW FACTOR CALCULATIONS

The following derivation of the equation shown as Equation 23 is taken from Reference 16. The solution of the contour integrals in Equation 23 for the specific case of the viewfactor from a differential element to a rectangle is then given.

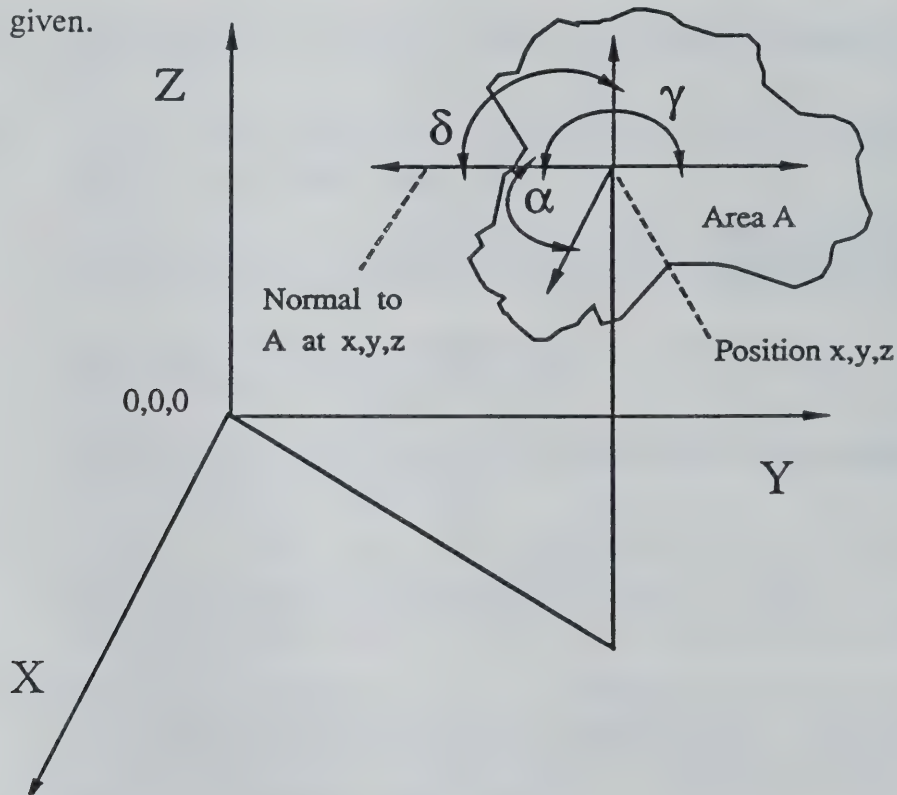


Figure 32: Geometry for quantities used in Stokes' theorem

Consider an arbitrary surface area A such as the one shown in Figure 32. The boundary of the surface must be piece-wise continuous and we define an arbitrary point on the surface to be located at the coordinates (x, y, z) . At the point (x, y, z) we construct a normal to the surface and define the angles be-

tween this normal and the x, y and z axes to be α , γ , and δ respectively. We now choose three arbitrary functions of x, y, and z which must be twice differentiable and call them P, Q, and R. Stokes' theorem then relates the integral of P, Q, and R around the boundary of the area A defined above (call this boundary C) and the integral of the functions over the surface A as:

$$\int_C (P dx + Q dy + R dz) = \int_A \left[\left(\frac{\partial R}{\partial y} - \frac{\partial Q}{\partial z} \right) \cos \alpha + \left(\frac{\partial P}{\partial z} - \frac{\partial R}{\partial x} \right) \cos \gamma + \left(\frac{\partial Q}{\partial x} - \frac{\partial P}{\partial y} \right) \cos \delta \right] dA \quad (17)$$

We now go back to Equation 6 from Section 2.1.2 and note that the integrand for the viewfactor F_{d1-2} is:

$$\frac{\cos \Theta_1 \cos \Theta_2}{\pi S^2} dA_2$$

where

$$S = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2 + (z_1 - z_2)^2}$$

Looking at the differential element dA_1 and a differential element on surface 2 as shown in Figure 33, we may define the two cosines in Equation 6 as:

$$\cos \Theta_1 = \frac{x_2 - x_1}{S} \cos \alpha_1 + \frac{y_2 - y_1}{S} \cos \gamma_1 + \frac{z_2 - z_1}{S} \cos \delta_1 \quad (18)$$

$$\cos \Theta_2 = \frac{x_1 - x_2}{S} \cos \alpha_2 + \frac{y_1 - y_2}{S} \cos \gamma_2 + \frac{z_1 - z_2}{S} \cos \delta_2 \quad (19)$$

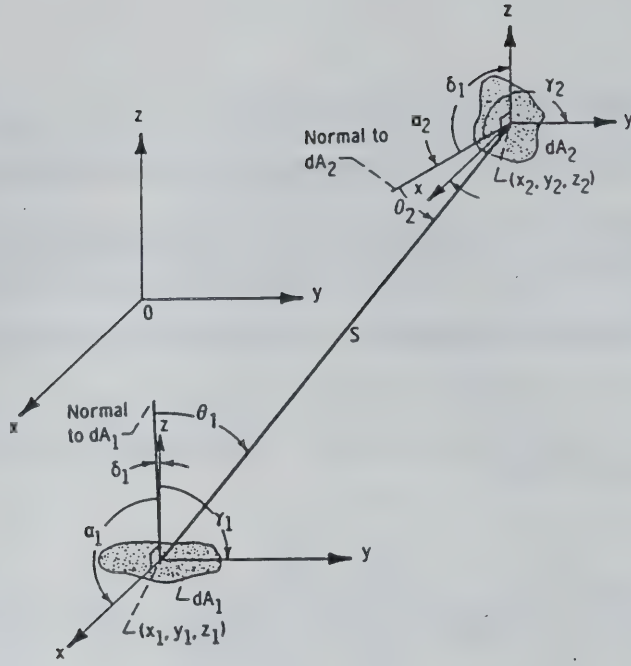


Figure 33: Geometry for contour integration.

If we now substitute Equations 18 and 19 into Equation 6, we obtain the following:

$$F_{d1-2} = \frac{1}{\pi} \int_{A_2} \frac{(x_2 - x_1) \cos \alpha_1 + (y_2 - y_1) \cos \gamma_1 + (z_2 - z_1) \cos \delta_1}{S^4} \times [(x_1 - x_2) \cos \alpha_2 + (y_1 - y_2) \cos \gamma_2 + (z_1 - z_2) \cos \delta_2] dA_2 \quad (20)$$

If we now define $l = \cos \alpha$, $m = \cos \gamma$, $n = \cos \delta$, and

$$f = \frac{(x_2 - x_1)l_1 + (y_2 - y_1)m_1 + (z_2 - z_1)n_1}{\pi S^4}$$

we may rewrite Equation 20 as:

$$F_{d1-2} = \int_{A_2} [(x_1 - x_2)fl_2 + (y_1 - y_2)fm_2 + (z_1 - z_2)fn_2]dA_2 \quad (21)$$

If we now compare Equations 21 and 17, we see that we may apply Stokes' theorem if we define the three relations:

$$\begin{aligned} \frac{\partial R}{\partial y_2} - \frac{\partial Q}{\partial z_2} &= (x_1 - x_2)f \\ \frac{\partial P}{\partial z_2} - \frac{\partial R}{\partial x_2} &= (y_1 - y_2)f \\ \frac{\partial Q}{\partial x_2} - \frac{\partial P}{\partial y_2} &= (z_1 - z_2)f \end{aligned}$$

Useful solutions of these three equations as given by [17] are the three following relations for P, Q, and R:

$$\begin{aligned} P &= \frac{-m_1(z_2 - z_1) + n_1(y_2 - y_1)}{2\pi S^2} \\ Q &= \frac{l_1(z_2 - z_1) - n_1(x_2 - x_1)}{2\pi S^2} \\ R &= \frac{-l_1(y_2 - y_1) - m_1(x_2 - x_1)}{2\pi S^2} \end{aligned}$$

If we now apply Stokes' theorem to Equation 21, we obtain the contour integral:

$$F_{d1-2} = \int_{C_2} (P dx_2 + Q dy_2 + R dz_2) \quad (22)$$

or, substituting the relations for P, Q and R into Equation 22:

$$\begin{aligned}
 F_{d1-2} = & \frac{l_1}{2\pi} \int_{C_2} \frac{(z_2 - z_1)dy_2 - (y_2 - y_1)dz_2}{S^2} \\
 & + \frac{m_1}{2\pi} \int_{C_2} \frac{(x_2 - x_1)dz_2 - (z_2 - z_1)dx_2}{S^2} \\
 & + \frac{n_1}{2\pi} \int_{C_2} \frac{(y_2 - y_1)dx_2 - (x_2 - x_1)dy_2}{S^2} \quad (23)
 \end{aligned}$$

where S is again

$$S = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2 + (z_1 - z_2)^2}$$

This is the general result for the viewfactor from a differential element to an arbitrary finite surface in space. For our purposes, we will define that arbitrary surface to be the radiating rectangular surface which we are using to model some of our heaters. Referring to Figure 13, we are setting up the problem by defining the origin of the coordinate system to be at the bottom left corner of the radiating rectangle, with the x and y axes parallel to the rectangle sides and the z axis perpendicular to the rectangle. The differential element is located at a position (x_1, y_1, z_1) in front of the rectangle with its normal in a plane parallel to the x axis. This is a restriction which we have put on the problem, i.e., the differential element is allowed to rotate across the length of the rectangle, but not in the plane of the height.

The orientation of the differential element is defined by an angle Φ which is the angle that the plane which the element lies in makes with the rectangle. Figure 34 shows a projection from above the radiating rectangle and element

showing the relationship between Φ , α_1 , and δ_1 (γ_1 is always $= 90^\circ$ since we have restricted rotation in the y plane). If we go back and look at Equation 23 and note that $\cos\gamma_1$ is always 0, that $\alpha_1 = (90 - \Phi)$, that $\delta_1 = (180 - \Phi)$, and that dz_2 will be zero around the contour of our rectangle, we get the following expression:

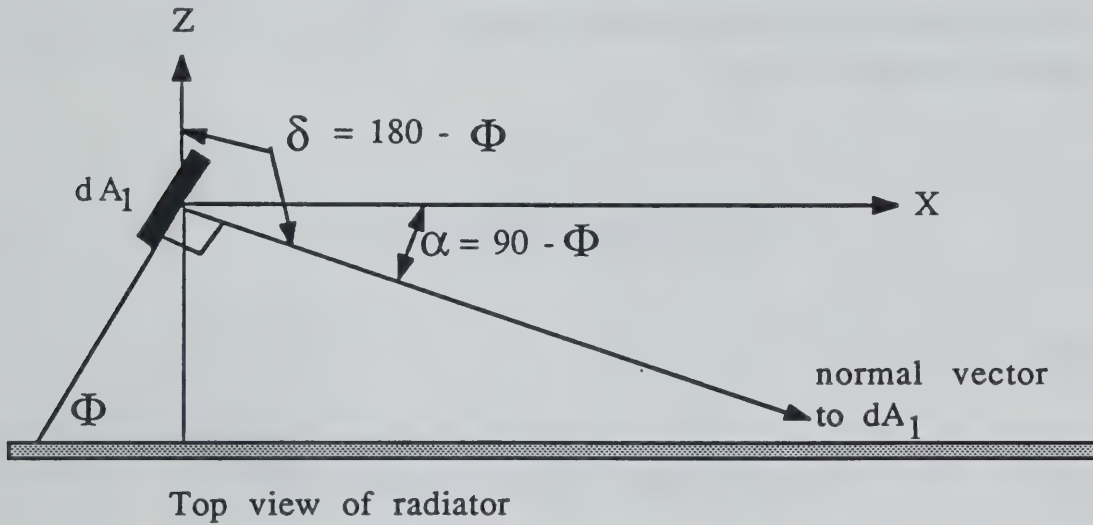


Figure 34: Two dimensional projection of the angle relationships

$$F_{d1-2} = \frac{\cos(90 - \Phi)}{2\pi} \int_{C_2} \frac{-z_1 dy_2}{S^2} + \cos \frac{(180 - \Phi)}{2\pi} \int_{C_2} \frac{(y_2 - y_1) dx_2 - (x_2 - x_1) dy_2}{S^2} \quad (24)$$

Each of these integrals will have four parts as we integrate around the four sides of the rectangle. Along these four sides of the rectangle contour, the following will apply:

- along side 1, $dy_2 = 0$, $0 \leq x_2 \leq LRAD$, and $y_2 = 0$.
- along side 2, $dx_2 = 0$, $0 \leq y_2 \leq WRAD$, and $x_2 = LRAD$
- along side 3, $dy_2 = 0$, $LRAD \leq x_2 \leq 0$, and $y_2 = WRAD$.
- along side 4, $dx_2 = 0$, $WRAD \leq y_2 \leq 0$, and $x_2 = 0$

These conditions give us six integrals which are non-zero, two from the first contour integral in Equation 24 and four from the second. Using the general indefinite integral solution

$$\int \frac{dx}{X} = \frac{2}{\sqrt{q}} \tan^{-1} \left(\frac{2cx + b}{\sqrt{q}} \right) ; q > 0$$

where

$$X = a + bx + cx^2 \quad \text{and} \quad q = 4ac - b^2$$

the first contour integral in Equation 24,

$$\int_{C_2} \frac{-z_1 dy_2}{S^2}$$

gives us the result:

$$\begin{aligned} \int_{C_2} \frac{-z_1 dy_2}{S^2} = & -z_1 \left[\frac{2}{\sqrt{q_1}} \left(\tan^{-1} \frac{2(WRAD) + a}{\sqrt{q_1}} - \tan^{-1} \frac{a}{\sqrt{q_1}} \right) \right] \\ & + \frac{2}{\sqrt{q_2}} \left(\tan^{-1} \frac{a}{\sqrt{q_2}} - \tan^{-1} \frac{2(WRAD) + a}{\sqrt{q_2}} \right) \end{aligned}$$

where

$$q_1 = 4(x_1 - LRAD)^2 + 4z_1^2, \quad q_2 = 4(x_1^2 + z_1^2), \quad \text{and} \quad a = -2y_1$$

The results of the second contour integral in Equation 24 are substantially similar and will not be given here.

Appendix B

NUMERICAL SOLUTION OF THE HEAT TRANSFER EQUATION

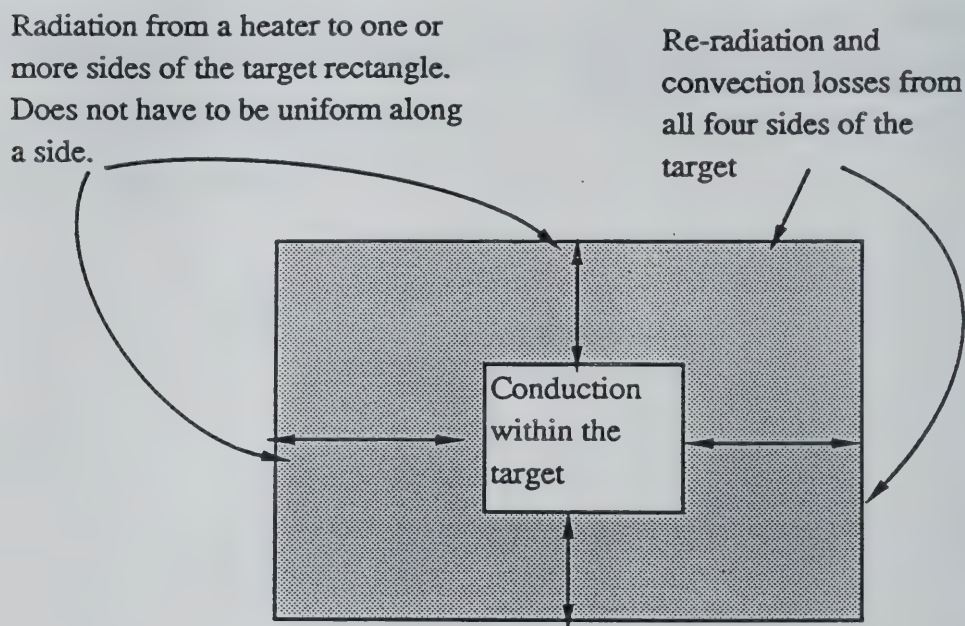


Figure 35: Geometry of the heat transfer problem

The geometry of the heat transfer problem is given in Figure 35. At the boundaries of the rectangular target object, there is heat transfer to and from the object by both convection and radiation, and conduction heat transfer into the object. The radiation received at the object's surface is from either the rectangular or cylindrical radiator and will be non-uniform along the object boundary. Re-radiation from the object's surface is modeled and is in two parts: 1) re-radiation back to the radiator and 2) re-radiation to the object's surroundings which are assumed to be at some uniform temperature specified by the user. The model has the ability to specify any one or more of the sides of the target object to be insulated which implements an adiabatic boundary condition on that (those) side(s). Radiation can not be received at an insulated

boundary. The convection heat transfer coefficient is specified by the user and is the same for all (non-insulated) sides.

The heat transfer equation for the problem, given as Equation 13 in Section 3.1.3. is:

$$\frac{1}{\alpha} \frac{\partial T_S}{\partial t} = \frac{\partial^2 T_S}{\partial x^2} + \frac{\partial^2 T_S}{\partial y^2}$$

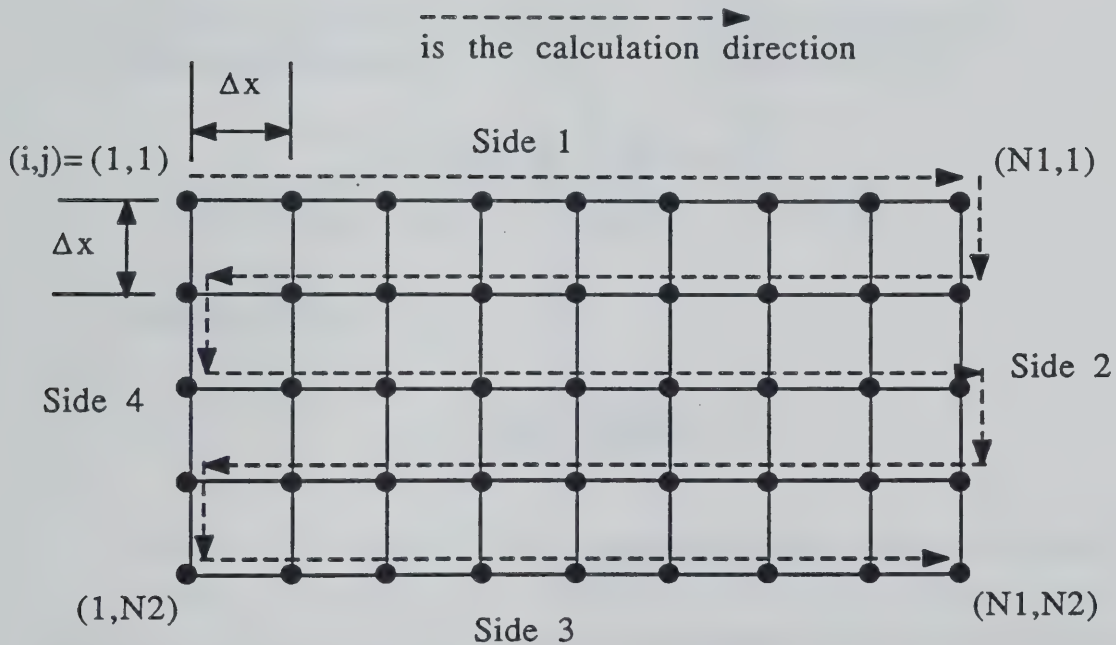


Figure 36: Discretization grid for the numerical computations.

In Figures 36 and 37, we show the discretization of the rectangular object for the numerical heat transfer calculations. Figure 36 shows the overall model and dimensions as well as the direction of iteration (dashed arrows). Figure 37 shows more detail of the model for the cases of a point on the surface of the object, on the corner of the object, and in the interior of the object. Note that in this two-dimensional model, the spatial step in both dimensions is required to be the same. This was done for ease of computation and does

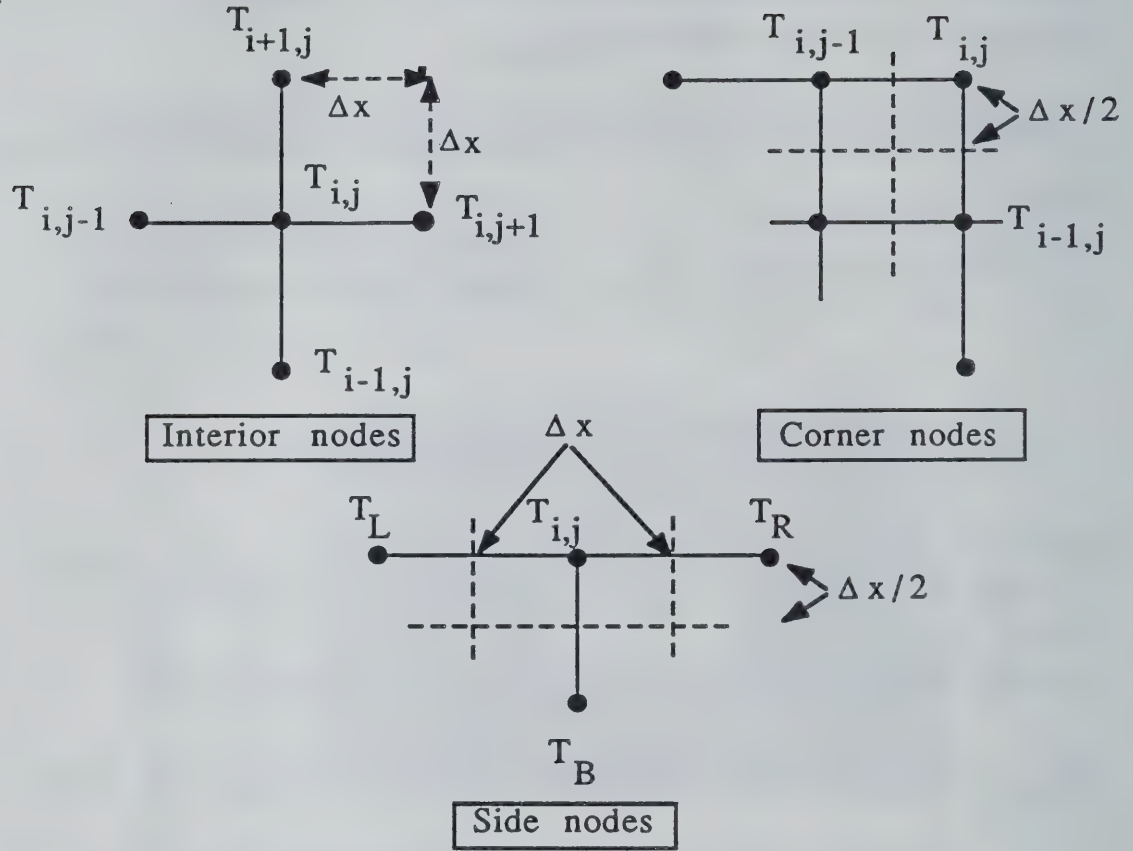


Figure 37: Details of the discretization.

not overly restrict the problem for our needs. A forward time difference model is used and a central space difference model. The simplest case is for the interior nodes where there is no convection or radiation transport to model. The difference equation for the interior nodes is:

$$T_{i,j} = \frac{1}{C} [T_{i,j+1} + T_{i,j-1} + T_{i+1,j} + T_{i-1,j}] + \frac{M}{C} T_{i,j,old} \quad (25)$$

where

$$M = \frac{\rho c_p \Delta x^2}{k \Delta t} \quad \text{and} \quad C = M + 4$$

$T_{ij,old}$ is the node temperature from the previous time step, Δx is the spatial distance step, Δt is the time step, c_p is the specific heat of the material, k is the thermal conductivity, and ρ is the density.

Referring to Figure 37 for the surface node, the surface point equations are derived using an energy balance as follows:

- Conduction at node i, j:

$$= - \left[\frac{2k}{\Delta x} T_{ij} - \frac{k}{2\Delta x} (T_L + T_R + 2T_B) \right]$$

- Convection at node i, j:

$$= -h(T_{ij} - T_{SURR})(INSUL)$$

where h is the convective heat transfer coefficient, T_{SURR} is the surroundings temperature, and "INSUL" is a factor which is equal to zero if the side is insulated and equal to 1 if it is not.

- Radiation at node i, j:

$$= [\varepsilon(FLUX) - F_{12}\sigma\varepsilon(T_{ij}^4 - T_{SURR}^4)](INSUL)$$

where ε is the object surface emissivity, FLUX is the external heat flux seen at the node, σ is the Stefan-Boltzmann constant, and F_{12} is the viewfactor from the node to the radiating object.

•

Energy storage in the solid at node i, j:

$$= \frac{\rho c_p \Delta x}{2\Delta t} (T_{ij} - T_{ij,old})$$

These terms are all signed so that Conduction + Convection + Radiation = Storage, and thus the final difference equation for a surface node is:

$$\begin{aligned} (INSUL)\sigma L T_{ij}^4 + \left(\frac{M}{2} + (INSUL)N + 2\right)T_{ij} = \\ \frac{1}{2}(T_L + T_R + 2T_B) + (INSUL)(NT_{SURR} + \\ L(FLUX) + (1 - F_{12})\sigma L T_{SURR}^4) + \frac{M}{2}T_{ij,OLD} \end{aligned} \quad (26)$$

where

$$N = \frac{h\Delta x}{k}, \quad \text{and} \quad L = \frac{\varepsilon\Delta x}{k}$$

The details of the corner difference equation derivation is substantially similar and will not be given here.

As may be noted from Equation 26, for any time step in the calculation, the solution for the temperature at node i, j is of the form:

$$AT_{ij}^4 + BT_{ij} = C$$

where A, B, and C are constants which are determined by other surrounding node temperatures at a previous iteration or physical parameters. This form does not lend itself to solution by standard iteration on the node field (e.g., Gauss-Seidel iteration), so we must resort to approximating these terms.

One method for quasilinearizing the fourth order term involves the following [38]:

$$\text{for } F(T) = T^4, \quad F(T) \cong (T_{ij,old})^4 + \left(\frac{\partial F}{\partial T_{ij,old}} \right) (T_{ij} - T_{ij,old}) \quad (27)$$

$$\text{and} \quad \left(\frac{\partial F}{\partial T_{ij,old}} \right) = 4T_{ij,old}^3$$

Using this approximation and the iteration scheme suggested in Figure 36 at each time step, we may calculate the temperature at each node in the grid as a function of time.

Appendix C

DATA ANALYSIS AND DISTRIBUTION ASSIGNMENTS

There are a number of physical and probabilistic parameters which need to be assigned probability distributions for use in the scenario calculations. The physical parameters fall into two groups: thermophysical parameters describing the target cloth and substrate, and dimensional and thermal output values for the four heater types in this study. The thermophysical target parameters are: the surface emissivity and spontaneous ignition temperature of the cotton/polyester cloth, and the density, thermal conductivity and specific heat of the substrate underneath the cloth. The dimensional and thermal output parameters for the heaters are the length and width of the radiating rectangle for the portable electric heater and the fixed, gas fueled heater, and the radius and cylinder height for the portable kerosene heater and the cylinder which we are using to approximate a wood stove. The total thermal output values of all the individual heater types must also be described. We must also investigate any correlations between the various parameters.

C.1 FABRIC PARAMETER DATA

The first two parameters which we will investigate are the surface emissivity and spontaneous ignition temperature of the cloth which we are modeling. The data we are using to assess the material properties have been presented in Table 11. The statistical characteristics of each set of data are given below as Table 15. The filtered and unfiltered sets of emissivity data do not show any real difference, but the values of the emissivity for charred cloth are overall higher than the other two. These values would be only applicable as the material approaches ignition and begins to smoke and char. Histograms of the three different measured emissivities are given as Figures 38-40.

TABLE 15

Statistics for fabric emissivity and ignition temperatures.

	Emissivity of fabric (unfiltered source)	Emissivity of fabric (red filter on source)	Emissivity of fabric (charred fabric)	Spont. Ignition Temp. (C)	Piloted Ignition Temp. (C)
N of cases	11	11	11	11	11
minimum	0.319	0.377	.0373	289.	285.
maximum	0.582	0.594	0.781	489.	376.
mean	0.444	0.478	0.624	394.4	323.8
stand. dev.	0.078	0.067	0.127	76.4	30.3

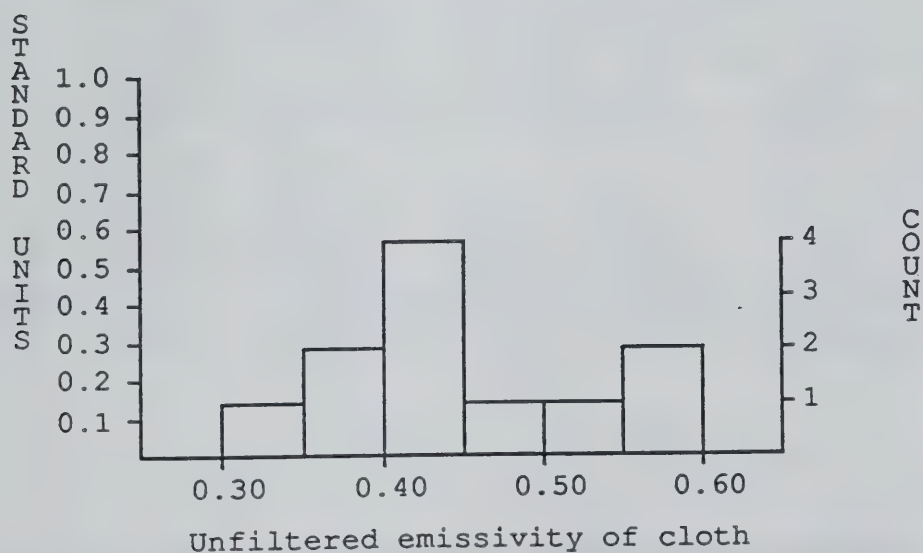


Figure 38: Histogram of data on the emissivity of target fabric with unfiltered heat source.

Of interest is whether the fabric emissivity and spontaneous ignition temperature are related to the makeup of the fabric (i.e., the percent cotton versus PE). A calculation of the data correlations (See Table 16) shows very little

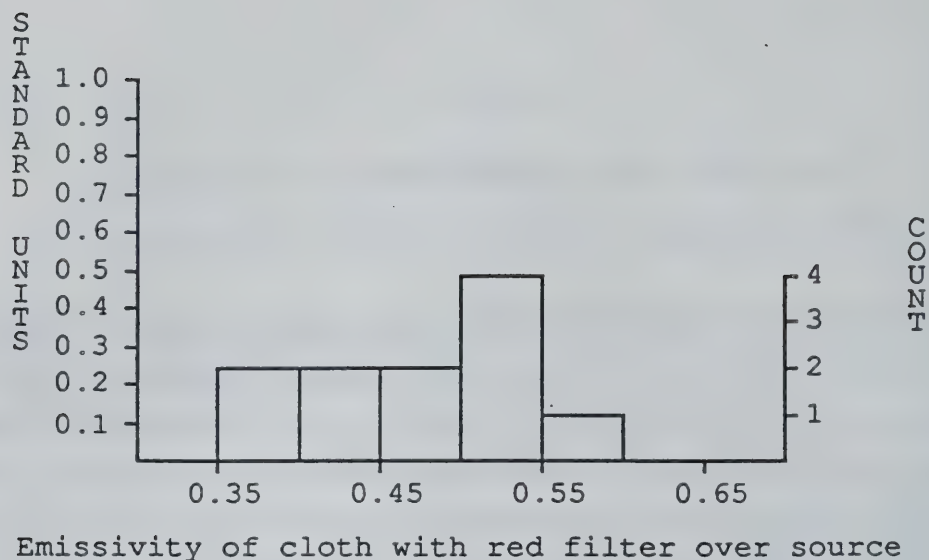


Figure 39: Histogram of data on the emissivity of target fabric with a red filtered heat source.

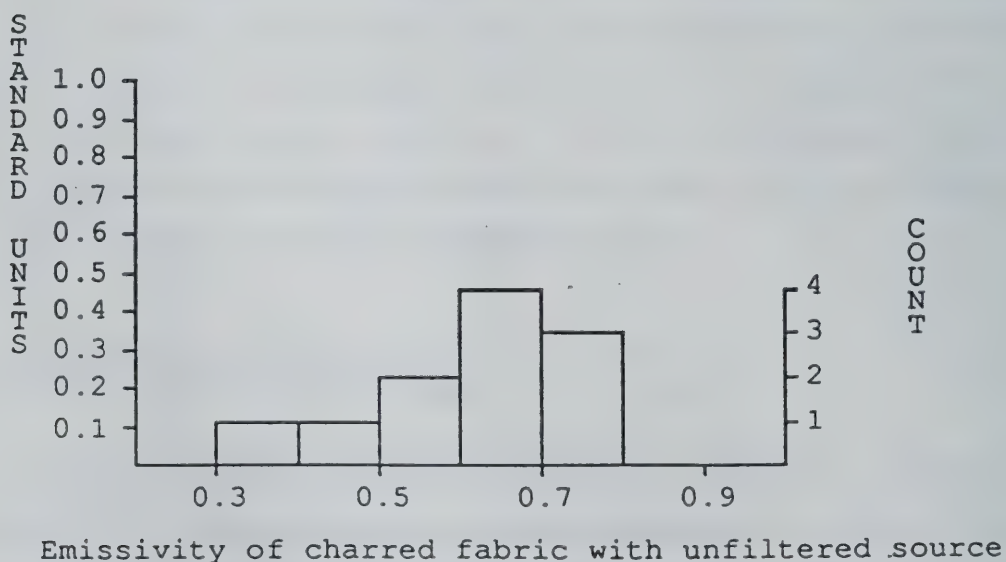


Figure 40: Histogram of data on the emissivity of charred target fabric.

relationship between the emissivity and the fabric composition and only a mild relation between the spontaneous ignition temperature and the fabric composition (correlations for the emissivities and the fabric content are all ≤ 0.4 and

for the spontaneous ignition temperature and the fabric content , it is only $\simeq 0.55$). A multiple scatterplot of the variables is shown in Figure 41. This plot is a way to see all the variables plotted against each other at once in order to examine their relationships. Since the percent cotton/polyester variables only have a few values, it is difficult to get a feel for the relationships from this plot, but if we look at an expanded version of the percent cotton versus spontaneous ignition temperature (Figure 42), it becomes somewhat easier.

TABLE 16

Correlations between data describing the target fabric.

	Emissivity of fabric (unfiltered source) (A)	Emissivity of fabric (red filter source) (B)	Emissivity of fabric (charred fabric)(C)	Spontaneous Ignition Temp. (°C) (D)	Piloted Ignition Temp. (°C) (E)
A	1.0				
B	0.781	1.0			
C	0.545	0.566	1.0		
D	0.073	0.297	0.850	1.0	
E	0.195	0.387	0.730	0.821	1.0
%COTTON	0.134	-0.234	-0.380	-0.552	-0.632
%PE	-0.134	0.234	0.380	0.552	0.632

From Figure 42, it is not easily evident whether a correlation really exists, although it is obvious where the mathematics of the calculation of the correlation given in Table 15 would give a non-trivial correlation. For 100 percent cotton fabric, there are a number of data points bunched in the low end of the ignition temperature range, but there are also two very high ignition temperatures. For lower cotton content fabrics, there are no corresponding low values. If it were not for the two high temperature values for 100 percent cotton, we might easily see a very great relationship between the ignition temperature

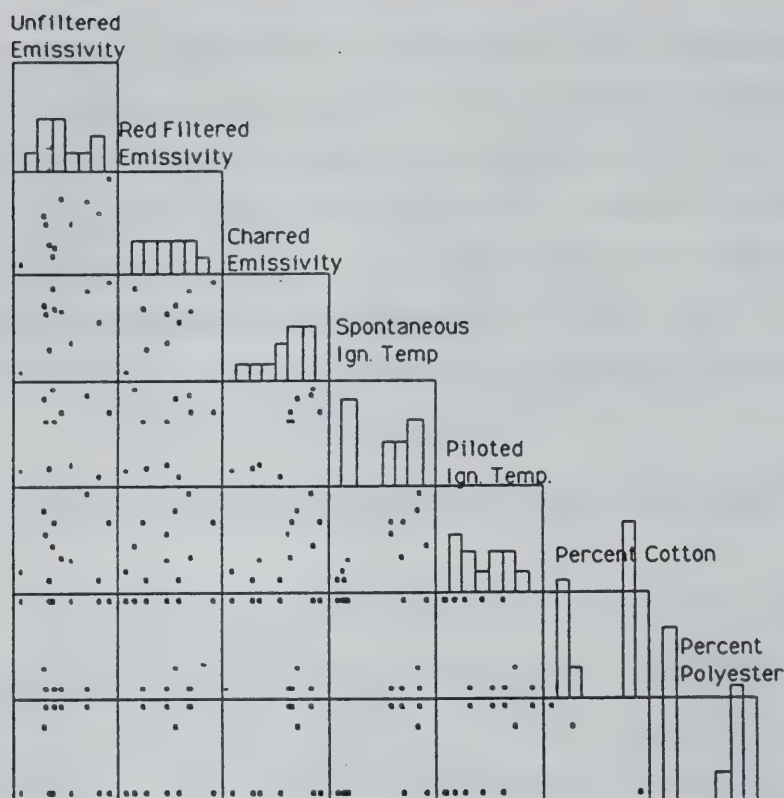


Figure 41: Multiple scatterplot of the fabric data.

and the cotton content. With the data we have, however, this conclusion is not warranted and we would look to other sources for the variation of ignition temperature if this were what we were looking for. From Figure 41, we can see this same occurrence for the charred fabric emissivity versus the spontaneous ignition temperature and we may draw the same conclusion about the correlation here.

Thus, since we have concluded that the variables describing the fabric emissivity and spontaneous ignition temperature are relatively independent of the fabric fiber content (for the fabrics which we are analyzing only) and of each

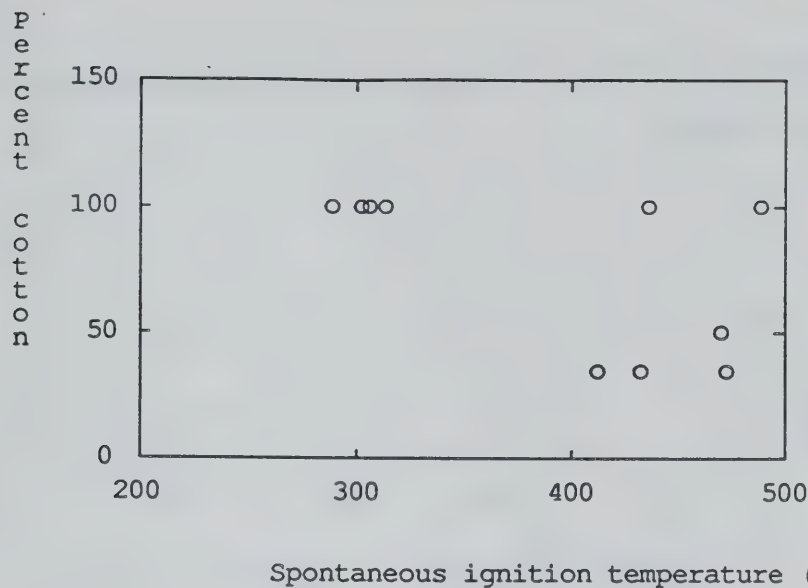


Figure 42: Fabric percent cotton versus spontaneous ignition temperature.

other, we may assign independent probability distributions to each variable to describe their values.

The emissivities thus far discussed were derived from a measured value of reflectivity using a 3400 K tungsten lamp as a heat source, which approximated the experimental conditions which were utilized in [28]. The values measured are, however, not indicative of the reflectivities which would be seen with the somewhat cooler heat sources with which we are dealing. Reference [31] suggests a range of 0.75 - 0.90 for the emissivity of "cloth" at 300 K. It has also been suggested [39] that a reasonable range of values for the emissivity of various fabrics should fall in the 0.85 - 0.95 range.

The above discussion therefore leads us to the distribution for the fabric emissivity shown in Figure 43. We will still take this distribution to be independent of the fabric fiber content since, lacking other information on this range of emissivities, we will assume that the properties of the emissivities from Table 11 may be translated to the new range of values. This distribution gives

most of its weight to the 0.85 - 0.95 range while acknowledging that some lower values may be possible.

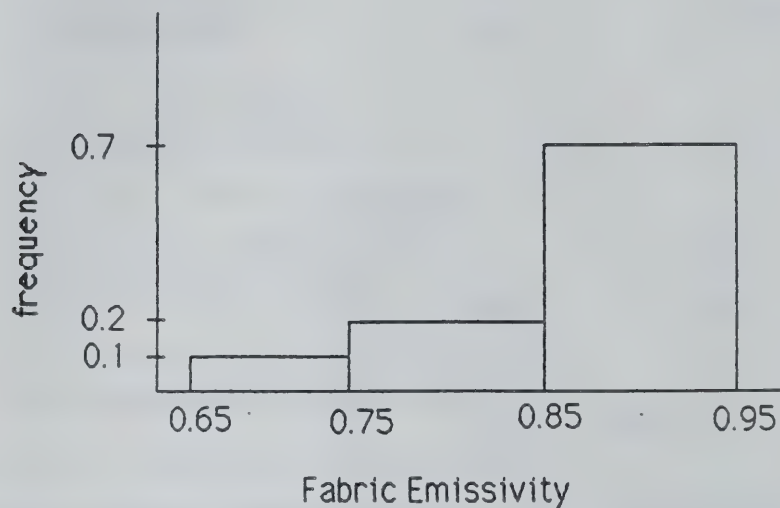


Figure 43: Histogram of the fabric emissivity

The histogram of the ignition temperature data (Figure 44) is somewhat less illuminating as to the shape of the data. This is in part due to the gap between approximately 330 and 400 C°. There is no physical reason to expect this gap in the data, but we will use this histogram as the distribution of the ignition temperature.

C.2 SUBSTRATE PARAMETER DATA

There are four "types" of substrate material which we need to consider: cotton, mixed fiber, and polyester batting materials and polyurethane foam (see discussion in Section 4.2.2.). The parameters needed to describe these materials are the density, specific heat, and thermal conductivity values of each. We have however, very little data on the properties of these materials. What data is available has been presented in Table 12.

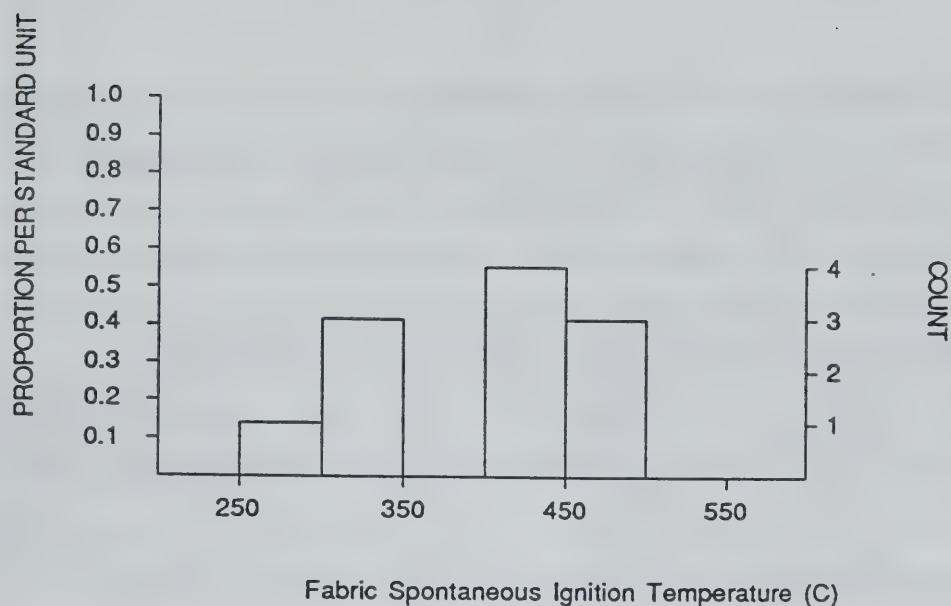


Figure 44: Histogram of the fabric spontaneous ignition temperature.

For most of the parameter ranges given in Table 12, we will take a uniform distribution over the range since we feel that it is equally likely that the true value will be anywhere in the ranges. Parameters which we will not do this for include the following: the thermal conductivity and the specific heat of polyurethane foam will be used as point values. The conductivity of the foam is close to that of air since it is mostly air, and the conductivity of air is well known, and our assumption that the specific heat of the foam is close to that of air requires the same assumption for the specific heat. Otherwise, we will assess uniform distributions on the parameter ranges given for cotton batting in Table 12, and also for the following polyester parameter ranges: thermal conductivity from 0.09 to 0.13 W/mK and the specific heat from 1050-1075 J/kgK since it is felt that the polyester data will adequately characterize the material, and 212 to 534 kg/m³ for the density since this data includes the polyester data and it is felt that the density values may still be high.

For the mixed fiber batting material, we will assume that it is a mixture of the cotton and polyester batting materials. We will also assume that when

they are mixed, there is no point to mixing them if there is not a substantial proportion of both materials in the mixture. Thus, we will assume that the proportions range from 35 percent polyester and 65 percent cotton to 65 percent polyester and 35 percent cotton. (These values are taken from common cotton/PE fabric mixtures, such as those for our fabric material.) This will give a range of thermal conductivity values from approximately 0.06 to 0.10 W/mK, specific heat values from 1086 to 1182 J/kgK, and densities from 100 to 370 kg/m³. We assess all of these ranges to have uniform distributions.

C.3 HEATER DIMENSION AND THERMAL OUTPUT DATA

We will discuss the four types of heaters independently.

C.3.1 *Electric Heater Data*

Table 6 gives the characteristics of the heaters which were surveyed in local California stores. From this data, Tables 17 and 18 show the statistics associated with each set of data and the calculated correlations between the variables. The relation of interest to us is between the power output and the heater dimensions. As can be seen in Figure 45, the lack of correlation shown in Table 18 for power versus area is borne out by the scatterplot of the data. It seems as though the area of the heater is more related to the heater physical design than the power output (at least for the range of electric heaters up to 1500 W).

Since we have concluded that the height, width and power output of electric heaters are uncorrelated variables, we may assign independent probability distributions to them. Figures 46- 48 show histograms of the three variables. Due to the small sample size and the way the data tends to gather together, we can only make crude guesses as to the true shapes of the distributions. The width data is reasonably well described by an lognormal distribution with

TABLE 17

Statistics for variables describing portable electric heaters.

	Power (W)	Width (cm)	Height (cm)	Area (m ²)
N OF CASES	39	39	39	39
MINIMUM	400.	10.	5.	.007
MAXIMUM	1500.	76.	61.	.099
MEAN	1145.9	18.6	16.6	.030
STD. DEV.	372.3	10.95	9.94	.019

TABLE 18

Correlations between variables describing electric heaters.

	Power	Width	Height	Area
Power	1.0			
Width	0.001	1.0		
Height	0.334	-0.113	1.0	
Area	0.244	0.721	0.590	1.0

mean equal to the sample mean of 18.6 cm and standard deviation of 11 (overlaid on Figure 46).

The heater height is well modeled by a lognormal distribution with mean = 17 cm and variance = 100 as shown in Figure 47

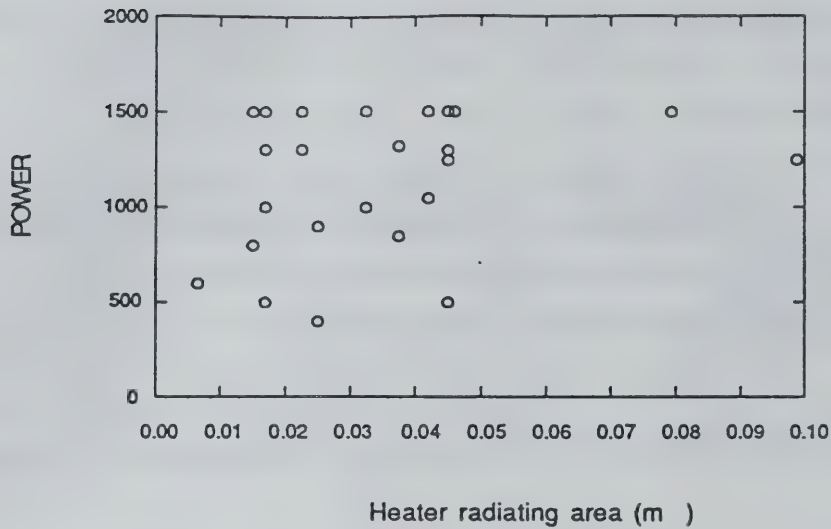


Figure 45: Electric heater surface area versus power output.

The histogram of the heater power shown in Figure 48 shows a bimodal distribution which it is difficult to model with standard distributions. Upon examining the data, however, especially the stem and leaf plot shown as Figure 49, we see that the heater output values are actually grouped into four separate groupings. (A stem and leaf plot shows the actual data values of the variable; the left column shows the last digit in which significant variation occurs, and the right column shows the next place for each data point. This means that the left column of the plot shows the hundredths place as the most significant for variation, and each digit on the right is one data point, e.g., the last row means 1500 on the left and fourteen data points in which the tens place was zero.) These groupings are approximately located at 500, 1000, 1300, and 1500 Watts. To describe the distribution of the heater power out-

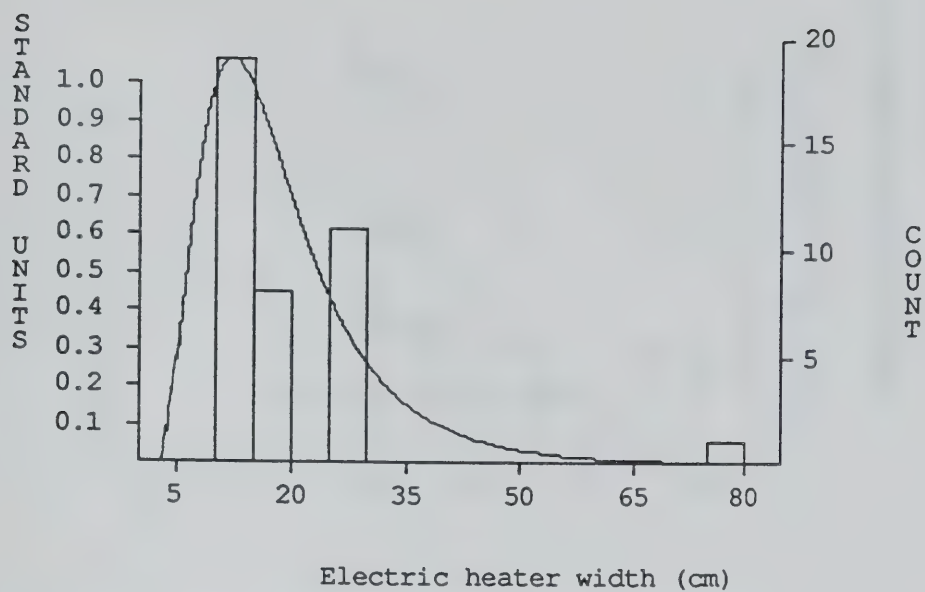


Figure 46: Histogram of the electric heater width data.

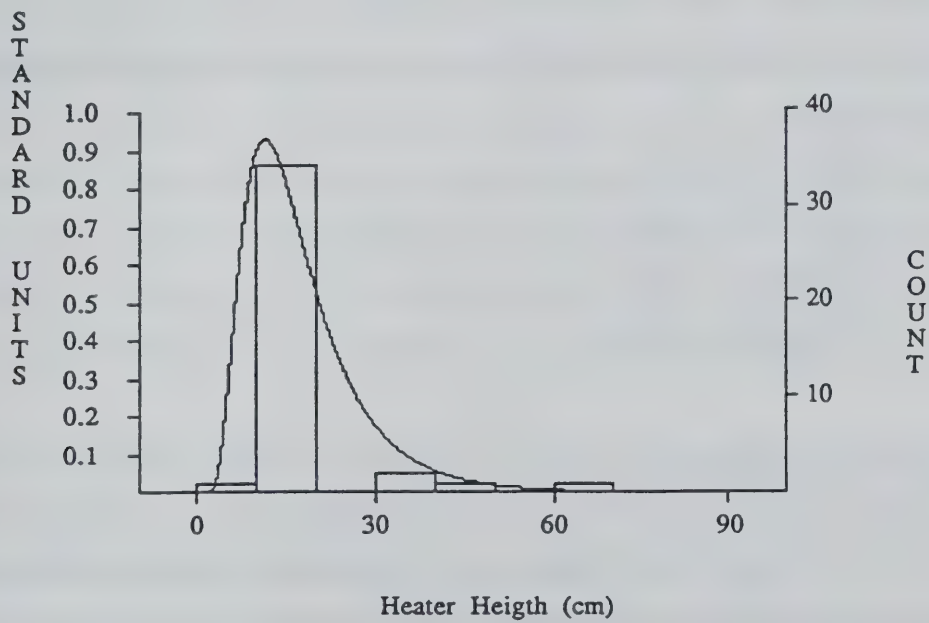


Figure 47: Histogram of the electric heater height data.

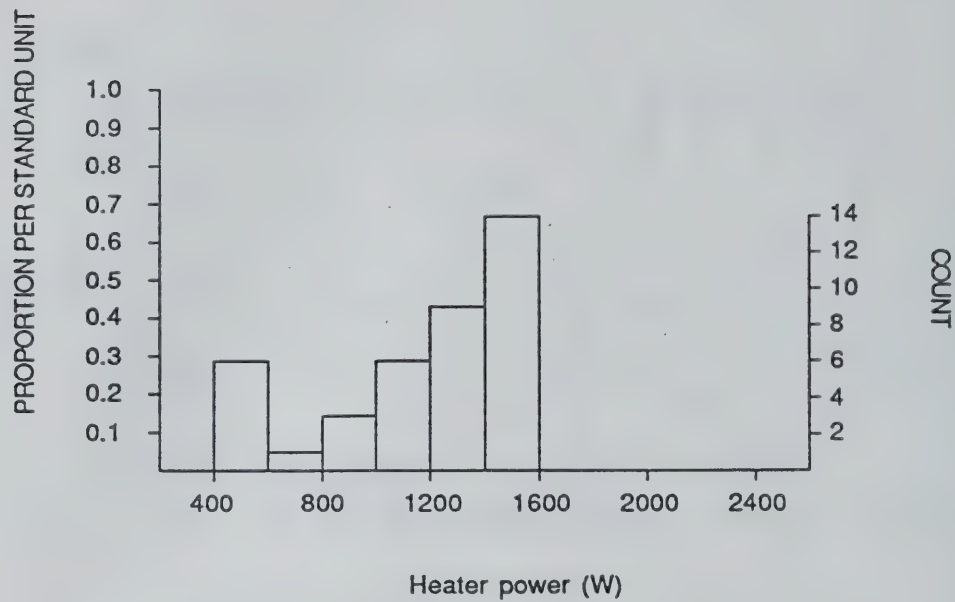


Figure 48: Histogram of the electric heater power data.

put, we will take these four points and assign probabilities to them on the basis of the sample fraction they include to form the discrete probability distribution having values:

$$\text{Pr}(500 \text{ W}) = 0.18$$

$$\text{Pr}(1000 \text{ W}) = 0.23$$

$$\text{Pr}(1300 \text{ W}) = 0.23$$

$$\text{Pr}(1500 \text{ W}) = 0.36$$

C.3.2 Gas Heater Data

The data shown in Table 7 give us only a very general feel for the dimensions of fixed, gas-fueled heaters and a fairly well- bounded, but small sample for the power output of the heaters. It seems as though shorter heaters tend to be wider than taller heaters, and heaters with more area tend to put out more heat. (This was not the case for electric heaters.) Since we are able to note

4	0
5	00000
6	0
7	
8	05
9 H	0
10	000005
11	
12	555
13 M	000022
14	
15 H	0000000000000000

Figure 49: Stem and leaf plot of the electric heater power output.

these possible trends, but do not have enough real data to substantiate them, we will have to make assumptions on the correlations.

To assign height and width measurements to our heaters, we will make the assumption that the width of the heater is linearly inverse correlated to the height such as in Figure 50. The minimum values of the height and width are chosen from the minimum height and width values from Table 7, subtracting 6 inches from the bottom and 1 inch around the other edges to compensate for non-radiating areas such as the pilot light and gas control valve area.

Since we have assumed that the height and width are completely correlated, we only have to define a distribution for one of them. We will define a uniform distribution for the width of the heater on the range 31 to 86 cm.

The power of the heater is not as simply described since Table 7 does show a higher output from the fourth heater in the table as compared to the second, and the fourth heater has a smaller surface area. Realistically, we do not know

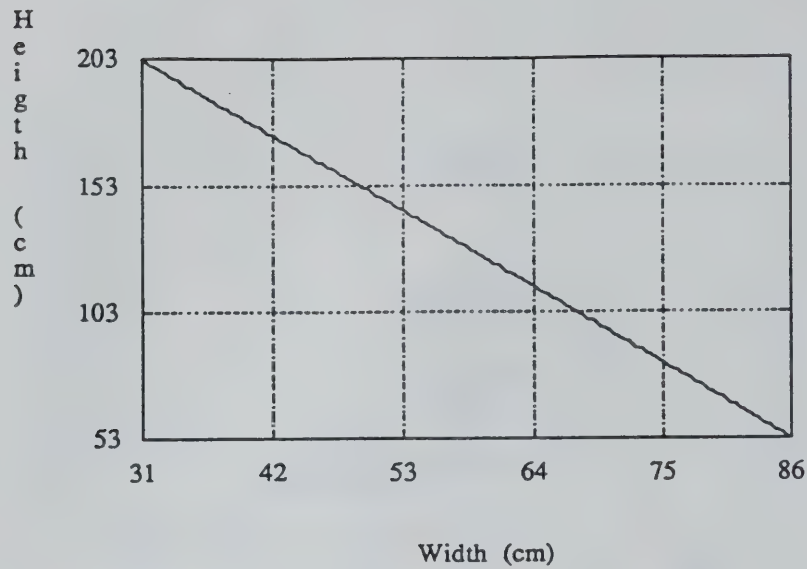


Figure 50: Assumed relation between gas heater height and width.

the relation between the power output and the heater size and we will assess the distribution of heater total power as being independent of the heater dimensions and uniform over the range 2800 - 13000 W. We will then couple this with a uniform distribution for the radiative fraction from 0.20 - 0.50. The resulting distribution of the gas heater radiative power is shown in Figure 51. The histogram underlying the distribution is from a Monte Carlo propagation of the product of the two distributions.

C.3.3 Kerosene Heater Data

Data on the dimensions and power outputs of kerosene heaters are very vague. We showed in Section 4.1.2.1 that the height and radius of the radiating portion of the heater range from 15 to 38 cm. and 7.5 to 12.5 cm. respectively. We feel that these dimensions probably will exhibit a uniform distribution on both height and radius, and in the absence of any data to establish a correlation between them, and no physical basis to assume one, we will assume that they are independent.

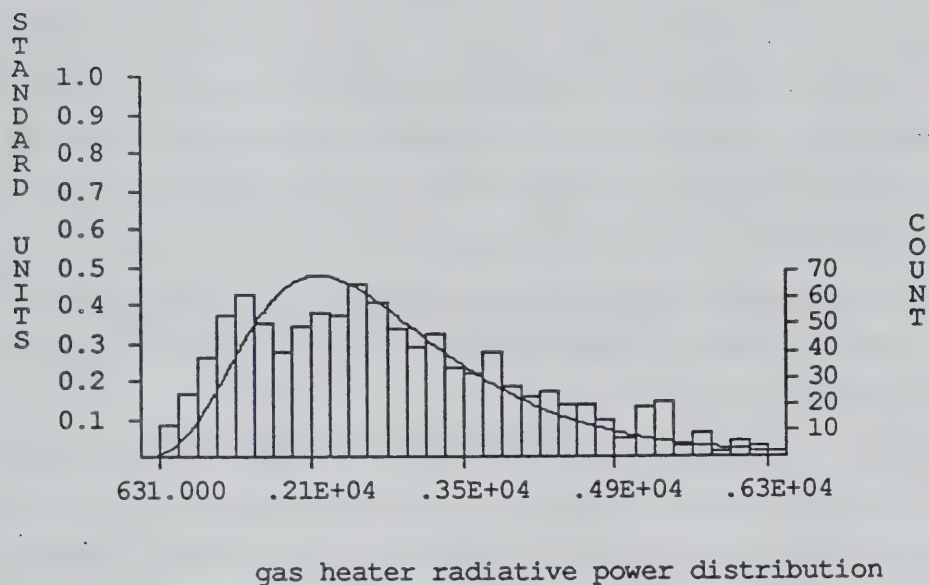


Figure 51: Gas heater radiative power distribution

The power output, however, seems to be mostly concentrated around 2 to 4 kW with a few larger heaters up to almost 6 kW. We will model this data with a lognormal distribution with mean=3270 and SD=923 as shown in Figure 52. We then couple this total power distribution with a uniform distribution of the radiative fraction of the power from 0.20 to 0.60, the result shown in Figure 53. The histogram underlying this distribution is from a Monte Carlo simulation of the product of the two distributions.

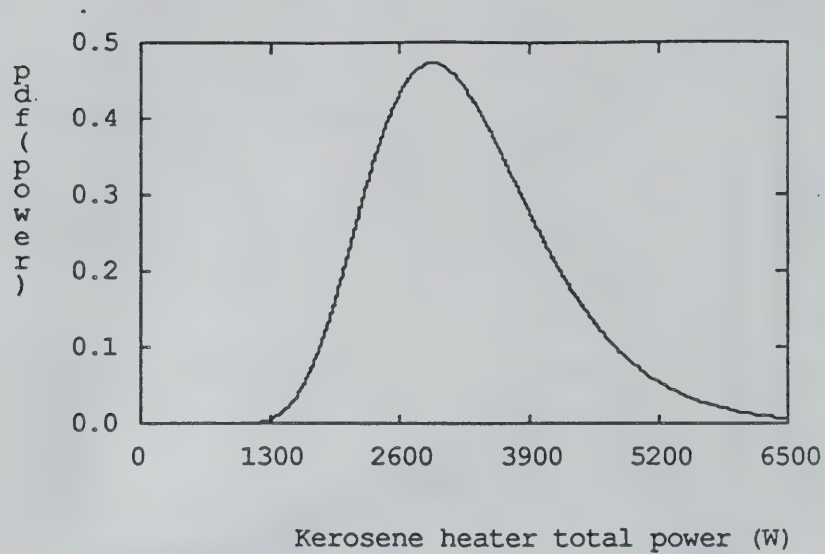


Figure 52: Distribution of the kerosene heater total power output

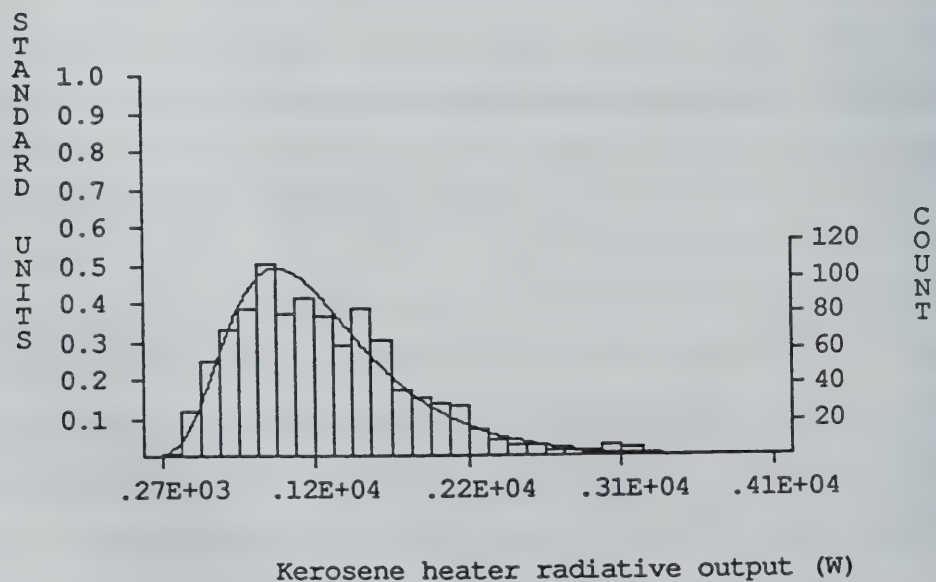


Figure 53: Distribution of the kerosene heater radiative power output

C.3.4 *Wood Stove Data.*

The 5 different stoves and 18 tests shown in Tables 9 and 10 give use a reasonable amount of data with which to assess the characteristics of a wood stove. As before with the other heater types, we are interested in distributions for the physical dimensions and power output of the heater and whether there are any correlations between these variables. We can see in Table 19 and Table 20 the statistics of the individual variables and the mathematical correlations between them. The heater area and the heat output values show a fair amount of correlation (≈ 0.7), but that is to be expected as we derived the heat output values from the stove temperatures and their areas. The temperature and heat outputs are highly correlated for the same reason (0.86 and 0.98). The real relation of interest is the area versus temperature correlation which is weak (0.24 for steady state and 0.58 for maximum). Figures 54 and 55 show little reason to doubt the weakness of this correlation. The 0.58 correlation is being driven by the three high data points at around 410 m^2 . The line on the steady state graph is a linear regression of the data and shows the weakness of the relationship here. Thus, since for the maximum temperature data, three points are responsible for the correlation (which is only 0.58) and there is no real correlation for the steady state data, we will assume that the size and the temperature of the stove are uncorrelated.

Since we have decided that the area and temperature are independent, it still remains to decide on the heat output distribution and its possible relationship to the area. It is expected that the heater output power will have some relation to the heater area since for any given range of temperatures, a larger heater will put out a higher range of heat fluxes than a small heater. However, the variations in the heater areas are not very large and the relation between the heater power and area is linear where the relation of the temperature to power is fourth order. Thus, the correlation effect between the area and power will be effectively overwhelmed by the independent temperature

TABLE 19

Statistics on the wood stove variables.

	HEATER AREA (cm ²)	STEADY HEAT OUTPUT (kW)	MAXIMUM HEAT OUTPUT (kW)	STEADY TEMP (°C)	MAXIMUM TEMP (°C)
N OF CASES	18	18	17	18	17
MINIMUM	296.000	8.016	12.291	278.000	377.000
MAXIMUM	414.000	33.512	129.446	436.000	733.000
MEAN	360.556	17.918	38.755	365.556	471.176
STD DEV	43.396	7.797	35.338	51.099	113.259

TABLE 20

Correlations between the wood stove variables.

	HEATER AREA	STEADY HEAT OUTPUT	MAXIMUM HEAT OUTPUT	STEADY TEMP	MAXIMUM TEMP
AREA	1.000				
SSHEAT	0.681	1.000			
MAXHEAT	0.660	0.037	1.000		
SSTEMP	0.243	0.857	-0.341	1.000	
MAXTEMP	0.575	0.008	0.974	-0.308	1.000

variable and we will also assume that the heater power is independent of the stove area.

On the basis of the above discussion, we can look at Figure 56 to gain some insight into the distribution of the heater power. This histogram includes both the steady state and overload temperature conditions with no attempt to assess the relative likelihood of either condition. It can be seen that the majority of the distribution is in the lower range with some values out on a longer tail. We can

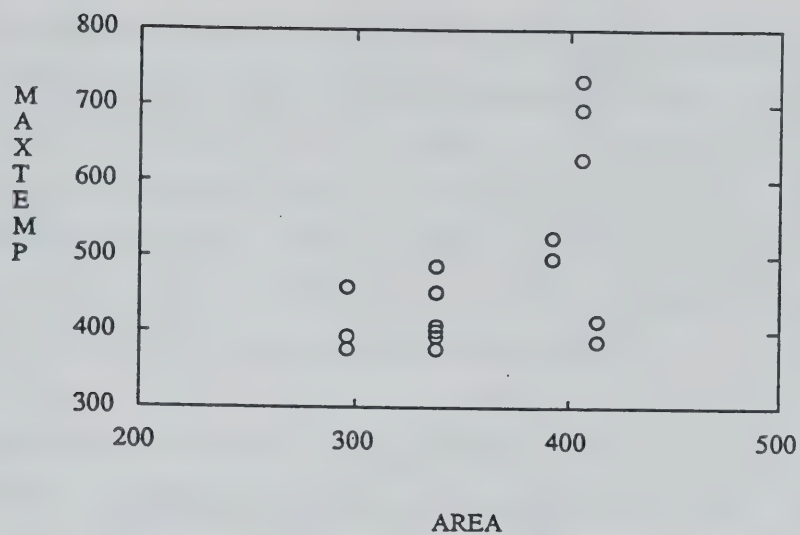


Figure 54: Maximum stove temperature versus stove surface area.

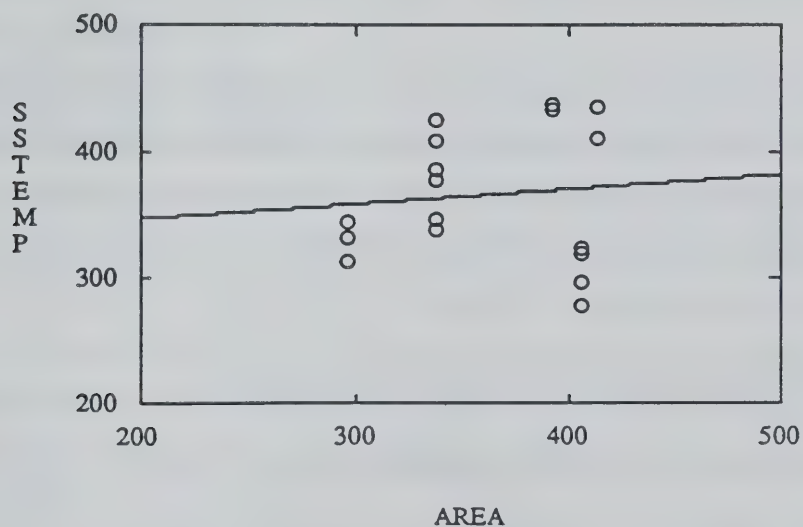


Figure 55: Steady state stove temperature versus stove surface area.

approximate this distribution by a lognormal distribution with mean = 27 kW and SD = 28 kW, shown as the overlaid curve in Figure 56

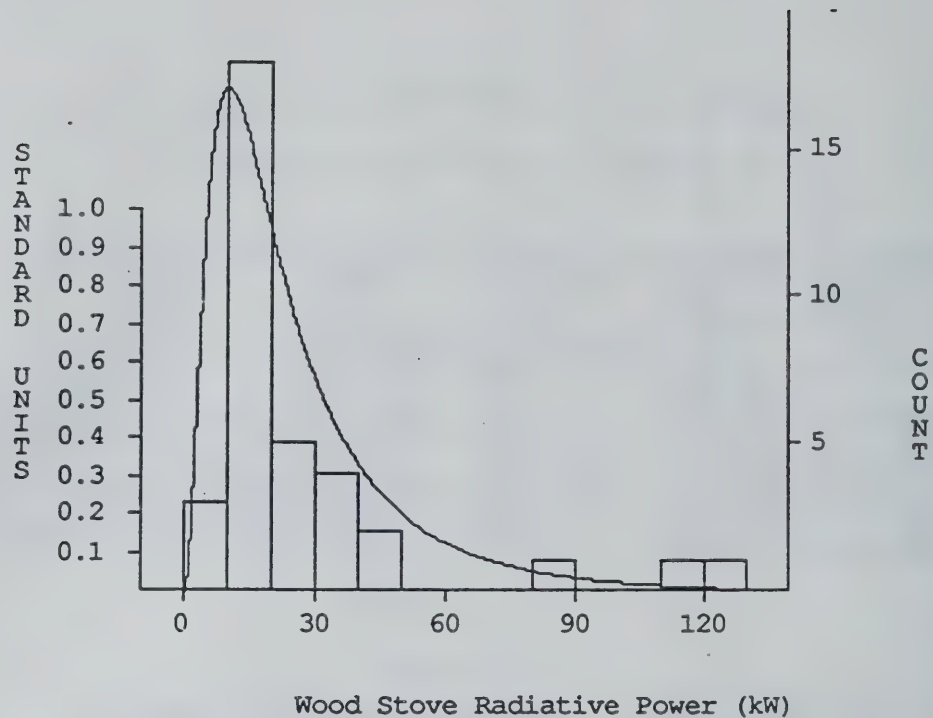


Figure 56: Distribution of the wood stove power output

The heater radius and height have only 5 values each and span ranges of 0.23 m to 0.39 m for the radius and 0.54 m to 0.79 m for the height. The values are reasonably well distributed over these ranges and thus we will assess a uniform distribution for both the height and radius of the wood stove.

C.4 PROBABILITY OF A CERTAIN SUBSTRATE

As discussed above, there are four different materials which we are considering to be possible substrates underlying our fabric. We need to figure out how likely it is that each of these different materials will be the substrate.

Data is available for a number of years in the past on the numbers of pieces of furniture which were manufactured with each of our different substrate types [40-41]. Actually, the data is for the number of pieces of furniture shipped and the relative amounts of materials consumed from which we may

arrive at the percent of items of furniture with each type of substrate as shown in Table 21. The actual number of total pieces of furniture is shown in the second column in Table 22 by year. However, not all of these pieces of furniture will still be in existence today, and as we can see from Table 21, the older types of furniture had quite different substrate distribution than newer furniture and this may have a substantial effect on the distribution of substrate types in existence in 1985 (the year we are evaluating).

A model from the Consumer Product Safety Commission (CPSC) for the life of consumer products [42] can be used to predict the product distribution in 1985. This model suggests that a piece of furniture from a specific year will have a life expectancy of 15 years with a standard deviation of 7 years. Thus, in 1985, only the very tail end of the distributions from years such as 1955, 1960, etc. will contribute to the totals and we will only be counting those substrate proportions which 'actually exist' (within the bounds of this very simple model). Computerizing this calculation gives us the results in Table 22 which are the the total number of pieces of furniture which survive from each year, the total of all these surviving units (339.4 million), the total from each year with a specific substrate and cellulosic covering, and the totals of each of these substrate types. From this we can see that approximately 36 percent of the substrates encountered will be cotton, 6.4 percent will be mixed fiber, 11 percent will be polyester and 43 percent will be polyurethane foam. We will use these values in the scenario calculations to set the proportions of the substrate types seen.

C.5 PROBABILITY OF SEEING A SPECIFIC HEATER TYPE

We must also know the relative number of heater units of the different types in order to assess the fraction of the scenarios in which each type of heater will be involved. Reference 8 gives us some useful numbers for the four heater types we are considering. These numbers are:

TABLE 21

Pieces of furniture manufactured by year with certain padding types [40-41]

UPHOLSTERED FURNITURE - MATERIAL CONSUMPTION, 1952-81

Production Year	Cover Fabric, %		Filling Material(Batting), %			
	Cellulosic	Thermoplastic	Cotton	Mixed Fiber	Polyester	PU Foam
1981	48	52	17	18	22	43
80	50	50	18	15	20	47
79	52	48	20	13	19	48
78	53	47	21	10	18	51
77	54	46	24	5	17	54
76	56	44	27	0	16	57
75	59	41	30	0	15	55
74	62	38	36	0	13	51
73	65	35	42	0	10	48
72	70	30	47	0	10	43
71	79	21	48	0	10	42
70	84	16	52	0	10	38
69	85	15	54	0	10	36
68	86	14	60	0	6	34
67	87	13	64	0	0	36
66	84	16	67	0	0	33
65	82	18	71	0	0	29
64	81	19	82	0	0	18
63	83	17	90	0	0	10
62	88	12	92	0	0	8
61	89	11	94	0	0	6
60	91	9	96	0	0	4
59	93	7	97	0	0	3
58	95	5	100	0	0	0
57	96	4	100	0	0	0
56	97	3	100	0	0	0
55	98	2	100	0	0	0
54	99	1	100	0	0	0
53	99	1	100	0	0	0
52	100	0	100	0	0	0

- 45.3 million portable electric units.

TABLE 22

Surviving furniture pieces by year and construction.

YEAR	# PRODUCED	PRCNT SURVIVED	# SURVIVED
1952	14.2	0.00498	0.1
1953	14.5	0.00773	0.1
1954	14.0	0.01119	0.2
1955	14.0	0.01628	0.2
1956	14.0	0.02294	0.3
1957	14.5	0.03097	0.4
1958	14.5	0.04306	0.6
1959	15.0	0.05861	0.9
1960	15.5	0.07731	1.2
1961	15.5	0.10019	1.6
1962	15.5	0.12950	2.0
1963	15.5	0.16003	2.5
1964	16.0	0.19833	3.2
1965	16.0	0.23884	3.8
1966	16.2	0.28778	4.7
1967	16.3	0.33909	5.5
1968	18.5	0.39233	7.3
1969	20.0	0.44863	9.0
1970	22.0	0.50858	11.2
1971	23.0	0.56626	13.0
1972	24.5	0.62267	15.3
1973	25.9	0.67636	17.5
1974	23.9	0.72958	17.4
1975	21.4	0.77657	16.6
1976	23.3	0.81647	19.0
1977	23.5	0.85600	20.1
1978	26.2	0.88875	23.3
1979	26.7	0.91561	24.4
1980	24.2	0.93842	22.7
1981	24.4	0.95589	23.3
1982	24.4	0.97205	23.7
1983	24.4	0.98330	24.0
1984	24.4	0.99299	24.2

TOTAL SURVIVING UNITS IN 1985 IS 339.4 MILLION

TOTAL SURVIVING UNITS WITH CELLULOSIC COVERS AND THE FOLLOWING SUBSTRATE				
YEAR	COTTON	MIXED FIBER	POLYESTER	PU FOAM
1952	0.1	0.0	0.0	0.0
1953	0.1	0.0	0.0	0.0
1954	0.2	0.0	0.0	0.0
1955	0.2	0.0	0.0	0.0
1956	0.3	0.0	0.0	0.0
1957	0.4	0.0	0.0	0.0
1958	0.6	0.0	0.0	0.0
1959	0.8	0.0	0.0	0.0
1960	1.0	0.0	0.0	0.0
1961	1.3	0.0	0.0	0.1
1962	1.6	0.0	0.0	0.1
1963	1.9	0.0	0.0	0.2
1964	2.1	0.0	0.0	0.5
1965	2.2	0.0	0.0	0.9
1966	2.6	0.0	0.0	1.3
1967	3.1	0.0	0.0	1.7
1968	3.7	0.0	0.4	2.1
1969	4.1	0.0	0.8	2.7
1970	4.9	0.0	0.9	3.6
1971	4.9	0.0	1.0	4.3
1972	5.0	0.0	1.1	4.6
1973	4.8	0.0	1.1	5.5
1974	3.9	0.0	1.4	5.5
1975	2.9	0.0	1.5	5.4
1976	2.9	0.0	1.7	6.1
1977	2.6	0.5	1.8	5.9
1978	2.6	1.2	2.2	6.3
1979	2.5	1.7	2.4	6.1
1980	2.0	1.7	2.3	5.3
1981	1.9	2.0	2.5	4.8
1982	1.9	2.0	2.5	4.9
1983	2.0	2.1	2.5	5.0
1984	2.0	2.1	2.6	5.0
TOTALS:	73.3061	13.3639	28.7074	87.9510 = 203.3

- 7.6 million fixed, gas-fueled heaters.

- 14.5-15.0 million portable, liquid fueled heaters.
- 12.7-12.9 million fixed area, solid fueled heaters.

We will use the relative proportions of the various heater types to set up the type of heater in our scenario calculations.

Appendix D

EXAMPLE PROBLEM USING THE COMPUTER MODEL

The code requires a variety of inputs from several different files:

general job data as shown below:

```
1 0 0 0 1      (#CHAIRS, #ELECTRIC/CHAIR,#KEROSENE/CHAIR
                  #GAS/CHAIR,#WOOD/CHAIR)
4              (#OF OUTPUTS DESIRED)
1 2 4 5        (KEY #'S OF OUTPUTS)
0.4 0.4 81     (TARGET LENGTH, WIDTH, #OF POINTS/SIDE)
8. 0 0 0 0 298. (HEAT TRANSFER COEFFICIENT,
                  INSUL(4) MATRIX, TSURROUND)
60.    75      (TIME STEP, # OF TIME STEPS)
```

Information on the characteristics of the target chair:

COVER	COVER	PADDING	PADDING	PADDING
EMISSIVITY	IGNITION	THERMAL	HEAT	DENSITY
	TEMP	COND.	CAPACITY	
0.90337	688.0	0.04761	1234.3	55.9

and information on the heater characteristics and the target position in relation to the heater:

STOVE HEIGHT	STOVE RADIUS	POWER (W)	TARGET HEIGHT	TARGET RADIUS (FROM STOVE)
0.54567	0.36541	32831.4	0.23064	0.12673

The outputs are (key numbers 1 through 5 respectively): the point-wise incident flux at each point along the target boundary, the viewfactor from each point on the target boundary to the heater, the temperature at every point in the target at each time step, the maximum side temperatures at each time step, and the time of ignition and temperature at ignition. The output for one scenario using a wood stove and the data shown above is given below. (Note that the temperature array for every point in the solid (output #3) is not given due to space constraints).

JOB NUMBER FOR CHAIR # 1: 1

WOOD

FLUX VALUES IN W/M² ALONG THE TARGET SURFACE

SIDE 1	SIDE 2	SIDE 3	SIDE 4
2518.1	0.0	280.0	16518.7
2375.8	0.0	257.7	16667.3
2243.3	0.0	237.8	16806.1
2119.8	0.0	220.0	16935.6
2004.6	0.0	204.0	17056.5
1897.2	0.0	189.5	17169.1
1796.9	0.0	176.5	17273.9
1703.2	0.0	164.7	17371.5
1615.6	0.0	153.9	17462.3

1533.7	0.0	144.1	17546.6
1457.1	0.0	135.2	17624.9
1385.2	0.0	127.0	17697.6
1317.9	0.0	119.4	17764.8
1254.8	0.0	112.5	17827.0
1195.5	0.0	106.2	17884.5
1139.8	0.0	100.3	17937.4
1087.5	0.0	94.8	17986.2
1038.2	0.0	89.8	18030.8
991.9	0.0	85.1	18071.7
948.2	0.0	80.8	18109.0
907.0	0.0	76.7	18142.7
868.1	0.0	73.0	18173.2
831.4	0.0	69.4	18200.5
796.7	0.0	66.2	18224.7
763.9	0.0	63.1	18246.0
732.9	0.0	60.2	18264.5
703.5	0.0	57.5	18280.2
675.6	0.0	55.0	18293.2
649.2	0.0	52.6	18303.5
624.2	0.0	50.3	18311.3
600.4	0.0	48.2	18316.5
577.8	0.0	46.2	18319.2
556.3	0.0	44.3	18319.3
535.9	0.0	42.6	18317.0
516.5	0.0	40.9	18312.1
498.0	0.0	39.3	18304.6
480.4	0.0	37.8	18294.6
463.6	0.0	36.3	18281.9
447.5	0.0	35.0	18266.5
432.2	0.0	33.7	18248.4
417.6	0.0	32.5	18227.5
403.7	0.0	31.3	18203.6
390.4	0.0	30.2	18176.7

377.6	0.0	29.2	18146.6
365.4	0.0	28.1	18113.3
353.7	0.0	27.2	18076.5
342.5	0.0	26.3	18036.0
331.8	0.0	25.4	17991.8
321.6	0.0	24.6	17943.6
311.7	0.0	23.8	17891.2
302.3	0.0	23.0	17834.3
293.2	0.0	22.3	17772.7
284.5	0.0	21.6	17706.0
276.2	0.0	20.9	17634.1
268.1	0.0	20.3	17556.5
260.4	0.0	19.7	17472.9
253.0	0.0	19.1	17383.0
245.8	0.0	18.5	17286.2
238.9	0.0	18.0	17182.3
232.3	0.0	17.5	17070.6
226.0	0.0	17.0	16950.8
219.8	0.0	16.5	16822.4
213.9	0.0	16.0	16684.7
208.2	0.0	15.6	16537.3
202.7	0.0	15.1	16379.7
197.4	0.0	14.7	16211.1
192.2	0.0	14.3	16031.1
187.3	0.0	13.9	15839.1
182.5	0.0	13.6	15634.5
177.9	0.0	13.2	15416.9
173.4	0.0	12.9	15185.7
169.1	0.0	12.5	14940.4
165.0	0.0	12.2	14680.8
160.9	0.0	11.9	14406.6
157.0	0.0	11.6	14117.7
153.3	0.0	11.3	13814.0
149.6	0.0	11.1	13495.7

146.1	0.0	10.8	13163.2
142.6	0.0	10.5	12816.9
139.3	0.0	10.3	12457.6
136.1	0.0	10.0	12086.3

VIEWFACTORS FROM POINTS ON THE TARGET TO
THE RADIATOR

SIDE 1	SIDE 2	SIDE 3	SIDE 4
0.096089	0.000000	0.010684	0.630342
0.090660	0.000000	0.009833	0.636012
0.085603	0.000000	0.009073	0.641309
0.080890	0.000000	0.008394	0.646253
0.076495	0.000000	0.007783	0.650863
0.072395	0.000000	0.007232	0.655160
0.068568	0.000000	0.006735	0.659162
0.064993	0.000000	0.006283	0.662887
0.061651	0.000000	0.005873	0.666350
0.058526	0.000000	0.005499	0.669569
0.055600	0.000000	0.005158	0.672556
0.052860	0.000000	0.004845	0.675327
0.050292	0.000000	0.004558	0.677894
0.047882	0.000000	0.004294	0.680268
0.045620	0.000000	0.004051	0.682460
0.043496	0.000000	0.003826	0.684481
0.041498	0.000000	0.003619	0.686340
0.039619	0.000000	0.003427	0.688045
0.037849	0.000000	0.003248	0.689605
0.036182	0.000000	0.003082	0.691026
0.034609	0.000000	0.002928	0.692315
0.033126	0.000000	0.002784	0.693477
0.031725	0.000000	0.002650	0.694519
0.030402	0.000000	0.002525	0.695444
0.029150	0.000000	0.002407	0.696256
0.027966	0.000000	0.002297	0.696961

0.026844	0.000000	0.002194	0.697559
0.025782	0.000000	0.002097	0.698055
0.024774	0.000000	0.002006	0.698450
0.023818	0.000000	0.001921	0.698747
0.022911	0.000000	0.001840	0.698945
0.022049	0.000000	0.001764	0.699048
0.021230	0.000000	0.001692	0.699053
0.020451	0.000000	0.001624	0.698963
0.019709	0.000000	0.001560	0.698776
0.019003	0.000000	0.001499	0.698492
0.018330	0.000000	0.001441	0.698109
0.017689	0.000000	0.001387	0.697625
0.017078	0.000000	0.001335	0.697039
0.016494	0.000000	0.001286	0.696348
0.015937	0.000000	0.001239	0.695549
0.015404	0.000000	0.001195	0.694638
0.014896	0.000000	0.001153	0.693611
0.014409	0.000000	0.001112	0.692463
0.013944	0.000000	0.001074	0.691190
0.013498	0.000000	0.001038	0.689786
0.013071	0.000000	0.001003	0.688243
0.012663	0.000000	0.000969	0.686556
0.012271	0.000000	0.000938	0.684716
0.011895	0.000000	0.000907	0.682716
0.011535	0.000000	0.000878	0.680545
0.011189	0.000000	0.000850	0.678193
0.010857	0.000000	0.000824	0.675651
0.010538	0.000000	0.000798	0.672906
0.010231	0.000000	0.000774	0.669945
0.009937	0.000000	0.000751	0.666756
0.009653	0.000000	0.000728	0.663323
0.009381	0.000000	0.000707	0.659631
0.009118	0.000000	0.000686	0.655664
0.008866	0.000000	0.000666	0.651404

0.008622	0.000000	0.000647	0.646833
0.008388	0.000000	0.000629	0.641931
0.008162	0.000000	0.000611	0.636678
0.007944	0.000000	0.000594	0.631054
0.007734	0.000000	0.000578	0.625037
0.007531	0.000000	0.000562	0.618605
0.007336	0.000000	0.000547	0.611737
0.007147	0.000000	0.000532	0.604410
0.006965	0.000000	0.000518	0.596604
0.006788	0.000000	0.000505	0.588298
0.006618	0.000000	0.000491	0.579475
0.006454	0.000000	0.000479	0.570117
0.006295	0.000000	0.000467	0.560211
0.006141	0.000000	0.000455	0.549748
0.005992	0.000000	0.000443	0.538722
0.005848	0.000000	0.000432	0.527133
0.005709	0.000000	0.000422	0.514988
0.005574	0.000000	0.000412	0.502298
0.005443	0.000000	0.000402	0.489084
0.005317	0.000000	0.000392	0.475374
0.005194	0.000000	0.000383	0.461204

MAXIMUM SIDE TEMPERATURES AT TIME = 60.0 SECONDS

SIDE 1	SIDE 2	SIDE 3	SIDE 4
--------	--------	--------	--------

580.6	301.7	518.6	654.4
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MAXIMUM SIDE TEMPERATURES AT TIME = 120.0 SECONDS

SIDE 1	SIDE 2	SIDE 3	SIDE 4
--------	--------	--------	--------

590.6	302.2	528.8	675.4
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MAXIMUM SIDE TEMPERATURES AT TIME = 180.0 SECONDS

SIDE 1	SIDE 2	SIDE 3	SIDE 4
--------	--------	--------	--------

591.5 302.3 530.0 680.0

MAXIMUM SIDE TEMPERATURES AT TIME = 240.0 SECONDS

SIDE 1 SIDE 2 SIDE 3 SIDE 4

591.8 302.4 530.4 682.3

MAXIMUM SIDE TEMPERATURES AT TIME = 300.0 SECONDS

SIDE 1 SIDE 2 SIDE 3 SIDE 4

592.0 302.4 530.6 683.8

MAXIMUM SIDE TEMPERATURES AT TIME = 360.0 SECONDS

SIDE 1 SIDE 2 SIDE 3 SIDE 4

592.1 302.4 530.8 684.8

MAXIMUM SIDE TEMPERATURES AT TIME = 420.0 SECONDS

SIDE 1 SIDE 2 SIDE 3 SIDE 4

592.2 302.4 530.9 685.6

MAXIMUM SIDE TEMPERATURES AT TIME = 480.0 SECONDS

SIDE 1 SIDE 2 SIDE 3 SIDE 4

592.2 302.5 530.9 686.2

MAXIMUM SIDE TEMPERATURES AT TIME = 540.0 SECONDS

SIDE 1 SIDE 2 SIDE 3 SIDE 4

592.3 302.5 531.0 686.7

MAXIMUM SIDE TEMPERATURES AT TIME = 600.0 SECONDS

SIDE 1	SIDE 2	SIDE 3	SIDE 4
--------	--------	--------	--------

592.3	302.5	531.0	687.1
-------	-------	-------	-------

MAXIMUM SIDE TEMPERATURES AT TIME = 660.0 SECONDS

SIDE 1	SIDE 2	SIDE 3	SIDE 4
--------	--------	--------	--------

592.3	302.5	531.1	687.5
-------	-------	-------	-------

MAXIMUM SIDE TEMPERATURES AT TIME = 720.0 SECONDS

SIDE 1	SIDE 2	SIDE 3	SIDE 4
--------	--------	--------	--------

592.3	302.5	531.1	687.8
-------	-------	-------	-------

MAXIMUM SIDE TEMPERATURES AT TIME = 780.0 SECONDS

SIDE 1	SIDE 2	SIDE 3	SIDE 4
--------	--------	--------	--------

592.4	302.5	531.1	688.1
-------	-------	-------	-------

IGNITION ON SIDE 4 AT TIME= 780.0 SECONDS AT 688.1 DEGREES K

SUMMARY OF CHAIR IGNITIONS:

THE NUMBER OF IGNITIONS ON CHAIR # 1 IS: 1 IN 1 TRIALS

U.S. DEPT. OF COMM. BIBLIOGRAPHIC DATA SHEET (See instructions)	1. PUBLICATION OR REPORT NO. NIST/GCR-89/562	2. Performing Organ. Report No.	3. Publication Date March 1989
4. TITLE AND SUBTITLE Fire Risk Analysis Methodology: Initiating Events			
5. AUTHOR(S) Mark D. Brandyberry and George E. Apostolakis			
6. PERFORMING ORGANIZATION (If joint or other than NBS, see instructions) University of California Dept. of Mechanical, Aerospace, and Nuclear Engineering Los Angeles, CA 90024-1597		7. Contract/Grant No. Grant No. 60NANB6D0649 8. Type of Report & Period Covered Final Report	
9. SPONSORING ORGANIZATION NAME AND COMPLETE ADDRESS (Street, City, State, ZIP) U.S. Department of Commerce National Institute of Standards and Technology Gaithersburg, MD 20899			
10. SUPPLEMENTARY NOTES ☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.			
11. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here) This report outlines a method for assessing the frequency of ignition of a consumer product in a building and shows how the method would be used in an example scenario utilizing upholstered furniture as the product and radiant auxiliary heating devices (electric heaters, wood stoves) as the ignition source. Deterministic thermal models of the heat transport processes are coupled with parameter uncertainty analysis of the models and with a probabilistic analysis of the events involved in a typical scenario. This leads to a distribution for the frequency of ignition for the product.			
12. KEY WORDS (Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons) electric heaters; ignition; risk analysis; stoves; upholstered furniture; wood			
13. AVAILABILITY ☒ Unlimited ☐ For Official Distribution. Do Not Release to NTIS ☐ Order From Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402. ☒ Order From National Technical Information Service (NTIS), Springfield, VA. 22161			14. NO. OF PRINTED PAGES 153 15. Price \$19.95

